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Seismic Hazard Characterization of 69 Nuclear Plant Sites East of the Rocky Mountains

Questionnaires

Prepared by D.L. Bernreuter, J.B. Savy, R.W. Mensing, J.C. Chen

Lawrence Livermore National Laboratory

Prepared for
U.S. Nuclear Regulatory
Commission

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Abstract

The EUS Seismic Hazard Characterization Project (SHC) is the outgrowth of an earlier study performed as part of the U.S. Nuclear Regulatory Commission's (NRC) Systematic Evaluation Program (SEP). The objectives of the SHC were: (1) to develop a seismic hazard characterization methodology for the region east of the Rocky Mountains (EUS), and (2) the application of the methodology to 69 site locations, some of them with several local soil conditions. The method developed uses expert opinions to obtain the input to the analyses. An important aspect of the elicitation of the expert opinion process was the holding of two feedback meetings with all the experts in order to finalize the methodology and the input data bases. The hazard estimates are reported in terms of peak ground acceleration (PGA) and 5% damping velocity response spectra (PSV).

A total of eight volumes make up this report which contains a thorough description of the methodology, the expert opinion's elicitation process, the input data base as well as a discussion, comparison and summary volume (Volume VI).

Consistent with previous analyses, this study finds that there are large uncertainties associated with the estimates of seismic hazard in the EUS, and it identifies the ground motion modeling as the prime contributor to those uncertainties.

The data bases and software are made available to the NRC and to public uses through the National Energy Software Center (Argonne, Illinois).

Abstract

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Table of Contents
Volume VII

PAGE

PAGE

Foreword

The impetus for this study came from two unrelated needs of the Nuclear Regulatory Commission (NRC). One stimulus arose from the NRC funded "Seismic Safety Margins Research Programs" (SSMRP). The SSMRP's task of simplified methods needed to have available data and analysis software necessary to compute the seismic hazard at any site located east of the Rocky Mountains which we refer to as the Eastern United States (EUS) in a form suitable for use in probabilistic risk assessment (PRA). The second stimulus was the result of the NRC's discussions with the U.S. Geological Survey (USGS) regarding the USGS's proposed clarification of their past position with respect to the 1886 Charleston earthquake. The USGS clarification was finally issued on November 18, 1982, in a letter to the NRC, which states that:

> "Because the geologic and tectonic features of the Charleston region are similar to those in other regions of the eastern seaboard, we conclude that although there is no recent or historical evidence that other regions have experienced strong earthquakes, the historical record is not, of itself, sufficient ground for ruling out the occurrence in these other regions of strong seismic ground motions similar to those experienced near Charleston in 1886. Although the probability of strong ground motion due to an earthquake in any given year at a particular location in the eastern seaboard may be very low, deterministic and probabilistic evaluations of the seismic hazard should be made for individual sites in the eastern seaboard to establish the seismic engineering parameters for critical facilities."

Anticipation of this letter led the Office of Nuclear Reactor Regulation to jointly fund a project with the Office of Nuclear Regulatory Research. The results were presented in Bernreuter et. al. (1985), and the objectives were:

1. to develop a seismic hazard characterization methodology for the entire region of the United States east of the Rocky Mountains (Referred to as EUS in this report).

2. to apply the methodology to selected sites to assist the NRC staff in their assessment of the implications in the clarification of the USGS position on the Charleston earthquake, and the implications of the occurrence of the recent earthquakes such as that which occurred in New Brunswick, Canada, in 1982.

The methodology used in that 1985 study evolved from two earlier studies LLNL performed for the NRC. One study, Bernreuter and Minichino (1983), was part of the NRC's Systematic Evaluation Program (SEP) and is simply referred hereafter to as the SEP study. The other study was part of the SSMRP.

At the time (1980-1985), an improved hazard analysis methodology and EUS seismicity and ground motion data set were required for several reasons:

- o Although the entire EUS was considered at the time of the SEP study, attention was focused on the areas around the SEP sites--mainly in the

Central United States (CUS) and New England. The zonation of other areas was not performed with the same level of detail.

- o The peer review process, both by our Peer Review Panel and other reviewers, identified some areas of possible improvements in the SEP methodology.

- o Since the SEP zonations were provided by our EUS Seismicity Panel in early 1979, a number of important studies have been completed and several significant EUS earthquakes have occurred which could impact the Panel members' understanding of the seismotectonics of the EUS.

- o Our understanding of the EUS ground motion had improved since the time the SEP study was performed.

By the time our methodology was firmed up, the expert opinions collected and the calculations performed (i.e. by 1985), the Electric Power Research Institute (EPRI) had embarked on a parallel study.

We performed a comparative study, Bernreuter et. al. (1987), to help in understanding the reasons for differences in results between the LLNL and the EPRI studies. The three main differences were found to be: (1) the minimum magnitude value of the earthquakes contributing to the hazard in the EUS, (2) the ground motion attenuation models, and (3) the fact that LLNL accounted for local site characteristics and EPRI did not. Several years passed between the 1985 study and the application of the methodology to all the sites in the EUS. In recognition of the fact that during that time a considerable amount of research in seismotectonics and in the field of strong ground motion prediction, in particular with the development of the so called random vibration or stochastic approach, NRC decided to follow our recommendations and have a final round of feedback with all our experts prior to finalizing the input to the analysis.

In addition, we critically reviewed our methodology which lead to minor improvements and we also provided an extensive account of documentation on the ways the experts interpreted our questionnaires and how they developed their answers. Some of the improvements were necessitated by the recognition of the fact that the results of our study will be used, together with results from other studies such as the EPRI study or the USGS study, to evaluate the relative hazard between the different plant sites in the EUS.

This report is comprised of eight volumes:

Volume I provides an overview of the methodology we developed as part of this project. It also documents the final makeup of both our Seismicity and Ground Motion Panels, and documents the final input from the members of both panels used in the analysis. Comparisons are made between the new results and previous results.

Volumes II to V provide the results for all the active nuclear power plant sites of the EUS divided into four batches of approximately equal size and of sites roughly located in the four main regions of the EUS. A regional discussion is given in each of Vols. II to V.

Volume VI gives some important sensitivity studies, in particular the sensitivity of the results to correction for local site conditions and G-Expert 5's ground motion model. Volume VI also contains a summary of the results and provides comparisons between the sites within a common region and for sites between regions.

Volume VII contains unaltered copies of the ten questionnaires used from the beginning of the 1985 study to develop the complete input for this analysis.

After the bulk of the work was completed and draft reports for Vols. I-VII were written, additional funding became available.

Volume VIII contains the hazard result for the 12 sites which had some structures founded on shallow soil. These results supplement the results given in Vols. II to V where only the primary soil condition at the site was used.

List of Abbreviations and Symbols

A	Symbol for Seismicity Expert 10 in the figures displaying the results for the S-Experts
ALEAS	Computer code to compute the BE Hazard and the CP Hazard for each seismicity expert
AM	Arithmetic mean
AMHC	Arithmetic mean hazard curve
B	Symbol for Seismicity Expert 11 in the figures displaying the results for the S-Experts
BE	Best estimate
BEHC	Best estimate hazard curve
BEUHS	Best estimate uniform hazard spectrum
BEM	Best estimate map
C	Symbol for Seismicity Expert 12 in the figures displaying the results for the S-Experts
COMAP	Computer code to generate the set of all alternative maps and the discrete probability density of maps
COMB	Computer code to combine BE hazard and CP hazard over all seismicity experts
CP	Constant percentile
CPHC	Constant percentile hazard curve
CPUHS	Constant percentile uniform hazard spectrum
CUS	Central United States, roughly the area bounded in the west by the Rocky Mountains and on the east by the Appalachian Mountains, excluding both mountain systems themselves
CZ	Complementary zone
D	Symbol for Seismicity Expert 13 in the figures displaying the results for the S-Experts
EPRI	Electric Power Research Institute
EUS	Used to denote the general geographical region east of the Rocky Mountains, including the specific region of the Central United States (CUS)

g	Measure of acceleration: 1g = 9.81m/s/s = acceleration of gravity
G-Expert	One of the five experts elicited to select the ground motion models used in the analysis
GM	Ground motion
HC	Hazard curve
I_o	Epicentral intensity of an earthquake relative to the MMI scale
I_s	Site intensity of an earthquake relative to the MMI scale
LB	Lower bound
LLNL	Lawrence Livermore National Laboratory
M	Used generically for any of the many magnitude scales but generally m_b, $m_b(Lg)$, or M_L.
M_L	Local magnitude (Richter magnitude scale)
M_b	True body wave magnitude scale, assumed to be equivalent to $m_b(Lg)$ (see Chung and Bernreuter, 1981)
$m_b(Lg)$	Nuttli's magnitude scale for the Central United States based on the Lg surface waves
M_S	Surface wave magnitude
MMI	Modified Mercalli Intensity
M_o	Lower magnitude of integration. Earthquakes with magnitude lower than M_o are not considered to be contributing to the seismic hazard
NC	North Central; Region 3
NE	North East; Region 1
NRC	Nuclear Regulatory Commission
PGA	Peak ground acceleration
PGV	Peak ground velocity
PRD	Computer code to compute the probability distribution of epicentral distances to the site
PSRV	Pseudo relative velocity spectrum. Also see definition of spectra below

Q — Seismic quality factor, which is inversely proportional to the inelastic damping factor.

Q1 — Questionnaire 1 - Zonation (I)

Q2 — Questionnaire 2 - Seismicity (I)

Q3 — Questionnaire 3 - Regional Self Weights (I)

Q4 — Questionnaire 4 - Ground Motion Models (I)

Q5 — Questionnaire 5 - Feedback on seismicity and zonation (II)

Q6 — Questionnaire 6 - Feedback on ground motion models (II)

Q7 — Questionnaire 7 - Feedback on zonation (III)

Q8 — Questionnaire 8 - Seismicity input documentation

Q9 — Questionnaire 9 - Feedback on seismicity (III)

Q10 — Questionnaire 10 - Feedback on ground motion models (III)

R — Distance metric, generally either the epicentral distance from a recording site to the earthquake or the closest distance between the recording site and the ruptured fault for a particular earthquake.

Region 1 (NE): North East of the United States, includes New England and Eastern Canada

Region 2 (SE): South East United States

Region 3 (NC): North Central United States, includes the Northern Central portions of the United States and Central Canada

Region 4 (SC): Central United States, the Southern Central portions of the United States including Texas and Louisiana

RP — Return period in years.

RV — Random vibration. Abbreviation used for a class of ground motion models also called stochastic models.

S — Site factor used in the regression analysis for G-Expert 5's GM model: S = 0 for deep soil, S = 1 for rock sites

SC — South Central; Region 4

SE — South East; Region 2

S-Expert — One of the eleven experts who provide the zonations and seismicity models used in the analysis

SEP	Systematic Evaluation Program
SHC	Seismic Hazard Characterization
SHCUS	Seismic Hazard Characterization of the United States
SN	Site Number
Spectra	Specifically in this report: attenuation models for spectral ordinates were for 5% damping for the pseudo-relative velocity spectra in PSRV at five frequencies (25, 10, 5, 2.5, 1 Hz).
SSE	Safe Shutdown Earthquake
SSI	Soil-structure-interaction
SSMRP	Seismic Safety Margins Research Program
UB	Upper bound
UHS	Uniform hazard spectrum (or spectra)
USGS	United States Geological Survey
WUS	The regions in the Western United States where we have strong ground motion data recorded and analyzed

Executive Summary

The results of this study, including Bernreuter et al. (1985), provide the NRC with the tools for characterizing the seismicity of the Eastern United States (EUS) and for describing the hazard at any location within the EUS. These tools are:

a. A data base of estimates of the seismicity of the EUS and appropriate ground motion (GM) models, based on expert opinions, in the form of:

   o A catalog of maps of zonation of the EUS along with estimates, including a measure of uncertainty in the estimate, of the zonation and seismicity of each zone.

   o A catalog of ground motion models including an assessment (weights) of their relative merits for propagating the motion from the source of motion to any location within the EUS.

b. A hazard methodology which uses the estimates in (a) to develop an estimate of the seismic hazard at any location in the EUS. The seismic hazard is described in terms of a hazard curve or a uniform hazard spectrum.

c. A data base of estimates of the seismic hazard computed at the 69 sites with either operating nuclear power plants or plants seeking a license.

The data base for characterizing the seismicity of the EUS has been developed from an elicitation of the opinions of experts in:

- o The geotectonic features and seismicity of the EUS.
- o Ground motion modeling.

The data base of results is described in detail below but consists of hazard curves at each site for PGA for the 15th, 50th and 85th percentile constant percentile hazard curves (CPHC), arithmetic mean hazard curves (AMHC) and best estimate hazard curves (BEHC). Uniform hazard spectra for various return periods are also included. All the results have been corrected for the site's local soil conditions. For the sites with structures founded on several different soil types, separate analyses have been performed for each soil type.

The motivation and history of this long study are summarized in the Foreword. As indicated in the Foreword, this report covering our methodology, data base, and results for the active nuclear power plants in the EUS is in eight volumes.

Volume I

We provide an overview of the methodology that we developed as part of the project to incorporate the judgement of experts and their quantification of the uncertainties about their input into a seismic hazard analysis using a

simulation approach. Our methodology relies heavily on our previous work, Bernreuter et al. (1985), and it highlights the improvements made in the final version of our methodology and computer codes.

In Section 2 and Appendix C we provide the basis for the seismic hazard analysis computer programs we developed to account for the uncertainty in the estimation of the seismic hazard at all EUS nuclear power plant sites using input from experts. This software incorporates a simulation approach to provide the experts with a relatively simple but effective way to express their uncertainty. The hazard methodology is based on a probabilistic model of the occurrence and distribution of magnitudes of earthquakes and the attenuation of the ground motion from a source to a site. It also includes modeling of local site effects.

In Section 3 we describe our elicitation process which was developed to give each expert sufficient flexibility to define his best estimate for the various parameters of interest, e.g., zonation, and to fully express his uncertainty. As part of our elicitation process, we assembled two groups of experts. One group, called our Seismicity Panel (S-Panel), is composed of experts in the seismic zonation of the EUS. The other group is composed of experts in ground motion estimation and we referred to them as our Ground Motion Panel (G-Panel). Our elicitation process also included a number of feedback loops to provide the experts with an understanding of the implications that their assumptions and models have on the computed hazards and to provide the experts with a simple formal way to update or change their input. In Section 3 and Appendix B we provide a summary of the final makeup of our panels and their input as it was used in our analysis.

Relative to the input data documented in our previous report, Bernreuter et al. (1985), the Ground Motion Experts extensively revised their input. Of the eleven S-Experts, three of them proposed totally new seismicity models, four of them retained their original models and the rest made minor changes.

In Section 4 a special effort is made to highlight the differences in results between our previous study, Bernreuter et al. (1985), and the present study. The important conclusion is, again, the stability of the seismicity modeling. We compared the new seismicity models with the previous ones by calculating the seismic hazard at the same ten sites and using the same ground motion models. The differences were quite small after combining over all the experts in spite of the fact that the results for some S-Experts changed significantly.

The final spectral ground motion models are significantly different from the previous (1985) set of models. This is due primarily to the fact that a new type of models have made its appearance, namely the random vibration, stochastic models.

Another important difference between the results of this analysis and the previous one, Bernreuter et al. (1985), is in the value of the minimum magnitude of the earthquakes contributing to the hazard which is magnitude 5 in the present study as opposed to 3.75 previously. The effect of this change is documented in the following Volumes II to V, by providing the best estimate seismic hazard created by the earthquakes of magnitude between 3.75 and 5.

Volume I contains in Appendix A the responses of the experts to the questionnaire on documentation. Appendix B provides all the final input data for the analysis, and Appendix C gives a detailed account of the methodology used in the analysis.

Volumes II-V

Because of the large number of sites for which results are presented we have broken them up into four batches of roughly the same number of sites. The results for each batch are presented in separate volumes - Volumes II-V. In selecting the sites for each batch an attempt was made to make a logical regional grouping of approximately the same size. Some compromises had to be made, particularly in batch 4. The sites in batch 1 correspond to the Northeast and batch 2 to the Southeast. Batch 3 covers the central part of the North Central region and Batch 4 is a potpourri of the remaining sites.

Volumes II to V have the same layout. In Section 1 there is a list of the sites included along with a map showing the location of the sites.

In each of Vols. II to V in Section 2, the results are presented individually for each site together with comments. Using a uniform format for each site (i.e., each section) we first present table 2.SN.1 (where "SN" stands for Site Number) providing the following information:

- o Soil category used in the analysis to correct for local site conditions

- o For each S-Expert table 2.SN.1 provides a listing of the four seismic zones which contribute most to the hazard in terms of the peak ground acceleration (PGA) at both lower PGA (0.125g) and at higher PGA (0.6g) values.

The contribution of various zones given in the table for each site is limited only to the contribution to the BEHCs.

The table is followed by ten or more figures, 2.SN.1 to 2.SN.*. The first three figures give various PGA hazard curves. As the seismic hazard results presented here account for earthquakes of magnitude 5 or above only, an additional set of calculations was made to provide an estimate of the seismic hazard created at each of the sites by the earthquakes of magnitude between 3.75 and 5. These results are given in Figs. 2.SN.4.

The next six figures give various 5 percent damped relative velocity spectra for five return periods. It should be noted that the spectral calculations have only been made at five periods, 0.04s, 0.1s, 0.2s, 0.4s and 1.0s and straight lines have been used to connect these points to get the shapes plotted.

For some sites additional figures are given to illustrate specific points. In particular, we found that at some rock sites for some S-Experts input the results were very sensitive to G-Expert 5's ground motion model. The reasons for this are discussed in each of the volumes.

In each of Vols. II to V in Section 3 we make comparisons between the results at the various sites included in these volume.

Volume VI

In Volume VI we discuss the important sensitivities found in the course of our analysis, we make regional comparisons between sites and summarize the conclusions we have reached.

In Section 2 we give a discussion of the sensitivity of the computed seismic hazard to several important aspects of the methodology used to estimate the ground motion. First, in Section 2.2 we present the results of a sensitivity study to show the effect that site correction has on the hazard. We selected the Limerick site and performed the analysis assuming that the site fell into each of our eight soil categories. We then compared the results from these eight separate analyses. This comparison gives the effect of site type on the hazard at the Limerick site. In an effort to generalize from these results, we found three pairs of sites that are distant from the Limerick site but each pair are relatively close together and have different site categories. By comparing the effect of site type on the hazard observed at these sites to the effect of site type observed at the Limerick site, we reached the conclusion that there did not appear to be a significant variation in the effect of site type introduced by the region the site is located in. This point is re-examined in Vol. VIII where we did find that for some sites, the ground motion amplification can be influenced by a combination of the regional seismicity and the ground motion models. It can be as much as 10 percent higher and as much as 8 percent lower than expected, had there been no regional effects.

In Section 2.3 we revisited the sensitivity of the results to the inclusion or non-inclusion of G-Expert 5's ground motion model. We identified four categories of sites: (1) rock with the hazard from distant zones with large earthquakes, (2) rock with the hazard primarily from local zones, (3) same as (1) except a soil site, and (4) same as (2) except a soil site. We found that the results were most sensitive to the inclusion or non-inclusion of G-Expert's 5 ground motion model for category (1), then followed by decreasing sensitivity for category (2), then category (3) and least sensitivity for category (4). Interestingly, we found the sensitivity of the median to the inclusion/non-inclusion of G-Expert 5's model was about the same for all four categories of sites.

In Section 2.4 we examined the reasons why our constant percentile uniform hazard spectra seemed to be high relative to the hazard curve for PGA. We concluded that the apparent disconnect between the PGA hazard and the spectral hazard was due to the correction for EUS conditions introduced into some of the ground motion models. These corrections suggest that typical EUS earthquakes have significantly more high frequency motion than assumed in either the R.G. 1.60 spectrum or the NUREG-0098 spectrum.

In Section 3 we compare the results between all sites. At the 0.2g level we found that typically at any site there is over two orders of magnitude uncertainty in the estimate of hazard (as measured by the difference between the 15th and 85th percentiles CPHCs). We also found that the spread of the

median probability of exceeding 0.2g PGA between the site with the lowest hazard and the site with the highest hazard is about 1.4 orders of magnitude.

We did not find large differences in the hazard between sites located at approximately the same distance (approximately 200 km) from the New Madrid seismic zone, as with sites located approximately the same distance from the Charleston seismic zone. We did find that the makeup of the hazard was different with nearby zones being more important for sites near the Charleston seismic zone than for sites near the New Madrid zones. Conversely, large distant earthquakes were more important for the New Madrid site than for the Charleston site.

We found that, <u>of the sites analyzed</u>, some sites in New England had the highest hazard. But it must be noted that the sites affected by the New Madrid and Charleston earthquake were at some distance from the source zones. Thus, if a site were to be located near these source zones, the hazard would be greater than found for the New England sites.

Some regional influence could be seen in the spectral shape, particularly at the longer periods. The spectral shapes for the sites near the New Madrid region had more long period energy than for sites located near Charleston or in New England. There were some differences at the short period end of the spectrum, but it was relatively small.

In Section 4 we present a number of conclusions reached during the course of this study, the most important of which are:

- Our estimates of the seismic hazard for any site in the EUS display a large uncertainty. Most individual experts have expressed significant uncertainties about their input. There is also a wide diversity in the opinion among experts.

- The median estimate of the seismic hazard appears to be relatively stable, both in time and between studies performed without systematic differences.

- Correction for local soil conditions is important and has a significant impact on the results.

- The results, particularly the arithmetic mean and best estimate estimators, are very sensitive to ground motion models with low attenuation, e.g., such as the model selected by G-Expert 5.

- There is a significant variation in the hazard across the EUS; e.g., the median estimate for the 10,000 year return period for the PGA varies from 0.08g to 0.33g.

<u>Volume VII</u>

Volume 7 is the text of the Questionnaires provided to the experts to develop the data base used in the analysis whose results are presented in this report. In all, ten questionnaires were designed and sent to the experts. They are the following:

Questionnaire 1 - Zonation Questionnaire (Q1)
Questionnaire 2 - Seismicity Questionnaire (Q2)
Questionnaire 3 - Questionnaire on Regional Self Weights (Q3)
Questionnaire 4 - Ground Motion Models Questionnaire (Q4)
Questionnaire 5 - Feedback-1 Questionnaire on Zonation/Seismicity (Q5)
Questionnaire 6 - Feedback-1 Questionnaire on Ground Motion Models (Q6)
Questionnaire 7 - Feedback-2 Zonation Questionnaire (Q7)
Questionnaire 8 - Documentation Questionnaire (Q8)
Questionnaire 9 - Feedback-2 Seismicity Questionnaire (Q9)
Questionnaire 10 - Feedback-2 Ground Motion Questionnaire (Q10)

Questionnaires Q1, Q2, Q3, Q5, Q7, Q8 and Q9 pertain to the S-Experts on zonation and seismicity. Q4, Q6 and Q10 pertain to the G-Experts.

The questionnaires are important to the reader for several reasons:

- The questionnaires allow the reader to understand exactly the questions that our experts were responding to. This provides the user of our methodology with sufficient information to judge--for specific applications--if additional information is needed.

- The questionnaires often have detailed explanations, comparisons and discussions which are needed to supplement the text of Vols. I-VI. In Vols I-VI we often made reference specific questionnaires rather than repeat a lengthy discussion or set of comparisons.

Volume VIII

After the completion of the analysis reported in Vols. II-V and summarized in Vol. VI, some additional funds became available. Because of the importance of the correction for local site conditions, it was determined that it would be most beneficial to use these funds to perform an analysis for the appropriate shallow soil category at the twelve sites which had most structures founded on rock but also had a few founded on shallow soil. These sites and their secondary soil categories are listed in Table 1.1 of Vol. VIII.

In Sections 2.1 to 2.12 we provide the results for the secondary soil category for the sites listed in Table 1.1. Using a uniform format for each site (i.e., each section) we first present Table 2.SN.1 (where "SN" stands for Site Number) providing the following information:

- Secondary soil category used in the analysis to correct for local site conditions.

- For each S-Expert the Table 2.SN.1 provides a listing of the four seismic zones which contribute most to the hazard in terms of the peak ground acceleration (PGA) at both lower PGA (0.125g) and at higher PGA (0.6g) values.

The contribution of various zones given in the table for each site is limited only to the contribution to the best estimate hazard curves (BEHCs).

The table is followed by Figs. 2.SN.1 to 2.SN.11 (SN = Site Number given in Table 1.1). The first three figures, Figs. 2.SN.1 - 2.SN.3 give various PGA hazard curves. Figure 2.SN.4 gives a comparison between the CPHCs for the shallow soil compared to the rock case. The next six figures, Figs. 2.SN.5 - 2.SN.10 give the 5 percent damped relative velocity spectra for five return periods. It should be noted that the spectral calculations have only been made at five periods, 0.04s, 0.1s, 0.2s, 0.4s, and 1.0s and straight lines have been used to connect these points to get the shapes plotted. Figures 2.SN.11 give a comparison between the 15th, 50th and 85th percentile CPUHS between the shallow soil case and the rock case.

In Section 3 we examine the regional variation of the effects of the site correction on the computed hazard. We also examine the sensitivity of the results to the choice of ground motion models, in particular, relative to the low attenuation model selected by G-Expert 5.

Our results show several interesting results:

- o There is some region-to-region variation and even site-to-site variation in the effect of correction due to the soil type at the site. This variation is found to be due to the combined and complex effects of interactions between the ground motion models and the seismicity and zonation models. It was found that for the three sites considered in batch 4 (Arkansas, Callaway and Duane Arnold), the site amplification ratio of PGA values for a fixed return period (soil/rock) is approximately equal to that of the case where Expert 5's ground motion is not used, that is, the resultant amplification is approximately 10% higher than what would be expected if all types of correction carried equal weight. For the other sites, in Region 1 and Region 2, the amplification factors vary by basically remaining within 5 percent of the value one would expect if the correction models of all five G-Experts carried the same weight.

  Now, if we compare the variations due to site correction in terms of probability of exceedance, one might be mislead in believing that the site effects could be very large.

  We found that the computed median hazard applicable for the structures founded in shallow soil range over a factor of 2 to over 5 higher than the median hazard applicable for structures founded on rock at the same site. Given this wide variation and the complex set of factors causing the variation, it is not possible to say positively that our results include the worst case.

- o It is clear from the results presented that it is not possible to approximately correct for site conditions by first computing the hazard at a site by considering it as a rock site and then introduce approximate correction factors, e.g., such as could be extracted from the sensitivity results given in Section 2.2 of Vol. VI.

- o Considerable caution must be exercised in trying to use the results given in this volume to extrapolate to other sites. There is a very complex interaction between the zonation, seismicity parameters and the correction for site type which has a significant impact on the computed hazard at any given site.

- The correction for site category is sensitive to the ground motion models used. If G-Expert 5's model is not included then it appears that there is a wider regional and site-to-site variation than when G-Expert 5's model is included.

FIRST QUESTIONNAIRE- ZONATION (Q1)

FIRST QUESTIONNAIRE- ZONATION (Q1)

1.0 INTRODUCTION

1.1 Background

The purpose of this project, intiated by the U.S. Nuclear Regulatory Commission (NRC), is to "develop a seismic hazard characterization for the region of the United States east of the Rocky Mountains." One task of the project is to assess the seismicity of this region and to describe it in a form which can be used as input to a seismic hazard analysis. The seismic parameters of interest are:

- o Seismo-tectonic zonation.
- o Rate of earthquake occurrence.
- o Distribution of earthquakes magnitudes.
- o Largest earthquake, i.e. upper magnitude cutoff.

Because it is difficult, or perhaps impossible, to precisely quantify such seismic parameters using only the sparse historical record, expert judgement is crucial. Thus, a panel of experts has been assembled. The membership of the panel is:

Dr. Peter W. Basham

Professor Gilbert A. Bollinger

Dr. Michael A. Chinnery

Mr. Richard J. Holt

Professor Arch C. Johnston

Dr. Alan L. Kafka

Professor James E. Lawson

Professor L. Tim Long

Professor Otto W. Nuttli

Dr. Paul W. Pomeroy

Dr. J. Carl Stepp

Dr. Anne E. Stevens

Professor Ronald L. Street

Professor M. Nafi Toksoz

Dr. Carl M. Wentworth

As a member of the panel you have been selected based on your knowledge of the seismicity of all or part of the Eastern United States (EUS). We wish to thank you for your willingness to participate in the deliberations of the panel.

Some of you are familiar with the approach that we are taking as you participated in an earlier study. That study was limited to the assessment of the seismic hazard at the nine oldest reactor sites in the EUS. This study represents a generalization of the earlier study in that: (1) the approach is modified to incorporate methodology improvements suggested by our reviewers, and (2) the area to be dealt with is the entire EUS east of the Rocky Mountain front, including the offshore regions along the east and Gulf coastlines.

For those of you not familiar with our approach, we have enclosed the overview report from the previous study and give below a brief description of the elicitation process and analyses planned. The elicitation process will be in three stages. The first stage will be the elicitation of the seismo-tectonic zonation. This is the object of this questionnaire. You will be asked to describe a base map which identifies all potential source zones for the EUS. Since you may be uncertain about the existence and shape of some of the zones, you will be asked to provide plausible alternatives to individual features of your base map. From this information, a set of mutually exclusive zonation alternatives for the entire region can be derived. An appropriate subset of these alternative maps can be used to assess the seismic hazard at a specific site.

The second stage of this study, a questionnaire will be sent to you in order to elicit your opinion on the occurrence rate and magnitude distributions. Ideally, you should use your own set of historical seismicity data. However, if you desire, we will provide you such data in the form of a catalog of historic events. This catalog is described in Appendix 1. Specifically, for each zone in your base map as well as for the alternate zones, you will be given (1) a listing of all earthquakes in the zone having magnitudes greater than some pre-specified minimum, and (2) a table giving the number of earthquakes in the zone as a function of magnitude[1]. You will then be asked to respond to questions designed to elicit your opinion, in light of the data, regarding the earthquake occurrence rate, upper magnitude cut-off and magnitude distribution.

Your responses will then be combined and cross-checked to assure consistency in the results. Also, the results will be used to compute the seimic hazard at various locaions in the EUS. These hazard assessments will be made available to you in the third stage of the elicitation process so that you may assess the physical reasonableness of the seimic parameters elicited in the first two stages of our process.

The third stage of the process will start with a general meeting of the panel, and at that time you will have the opportunity to review results based on your input, as well as the results from the other panel members. In order to ensure anonymity, each panel member's results will be identified by some code which only that panel member will know. In addition, at the meeting we will discuss:

1. We use the term magnitude as a general term referring to size, not as a specific measurement.

1. the models and approximations that we introduced to put your results into a form suitable for input into our hazard analysis;

2. the parameters which contribute the most to the uncertainty in the predicted seismic loading at the selected sites and to which the results are most sensitive; and

3. those areas which may need to be more carefully considered by the panel members.

After this meeting we will formally request that you revise your original responses if appropriate.

1.2 Description of the Seismic Hazard Analysis

Given source zone configurations and seismicity information from the first two questionnaires, along with an attenuation model, we can compute a hazard curve for any site in the EUS and any time period T. The hazard curve at a site is defined here to be the probability, P(A>a), that the maximum value of peak ground acceleration, A, induced at the site by earthquakes occurring within a T-year period exceeds the value a. Graphically, a typical hazard curve, plotted on a semi-logarithm scale, is given in Figure 1.1.

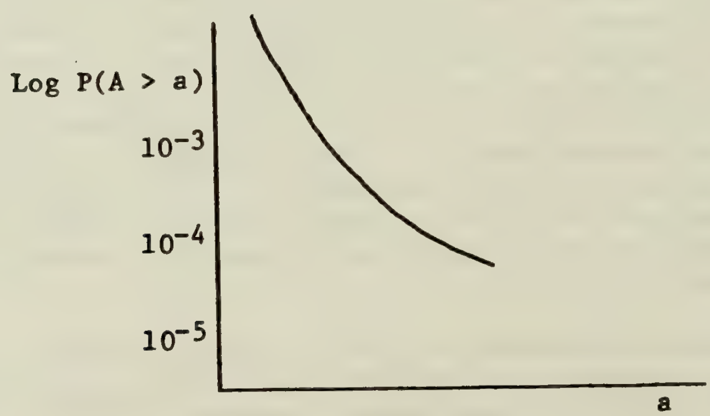

Figure 1.1 Typical Hazard Curve at a Site

To develop a hazard curve at a site, it will be necessary for us to adopt certain models to describe seismicity. From the responses to this questionnaire we will be able to develop a collection of maps (alternative source zone configurations for the EUS) for each expert. Given a map, we model the occurrence of earthquakes within each zone, where attention is restricted to earthquakes with magnitudes exceeding some pre-specified minimum, M_m. Following the standard hazard analysis practice, we assume that the occurrence of earthquakes can be approximated by a Poisson process.

You will be asked, in the second questionnaire, to estimate the space-time rate of occurrence, which is assumed constant within a zone, but which may vary from zone to zone. Given an earthquake, it is then necessary to model the magnitude distribution. You will be asked to model the magnitude-recurrence relationship for each zone and also to estimate the values of the parameters of the model (e.g., a linear model with an intercept and a slope as parameters). In addition, you will be asked your opinion about the existence of a physical upper bound on earthquake magnitudes. If you feel that you cannot give such an upper bound, or if you feel that the bound is so large as to be of no practical importance, then we will model the distribution of magnitudes with an upper limit equal to the largest observable value on your chosen measurement scale (e.g., XII on MMI scale). On the other hand, if you specify an upper magnitude cutoff, M_u, the range of the magnitude distribution will be restricted to the interval $[M_m, M_u]$. Your magnitude-recurrence model and your upper magnitude cutoff value will be combined to model the distribution of magnitudes for each zone.

Another essential ingredient in seismic hazard analyses is the attenuation model which relates peak ground acceleration at a site to earthquake magnitude and source-site distance. This portion of the project is not concerned with the choice of attenuation model. A second panel is being formed to assist in the selection of appropriate attenuation models and to estimate the parameters of the model.

The seismicity information for each expert is combined with the attenuation model to develop a "best estimate" hazard curve for each expert. Variations in the source zone configurations and uncertainty in the seismicity parameters will be combined to develop bounds for the hazard curve which reflect your level of confidence in your responses.

1.3 Discussion

Information about the seismicity in the EUS is available both in the form of recorded events (i.e., data) and in knowledge, held by individuals like yourselves, about the tectonic and geologic properties of the region which affect seismicity. Thus, it is appropriate to combine these two sources of information when characterizing seismic hazards in the EUS. Methods exist for analytically combining data with opinions, however, in this project we are relying on your abilities to assimilate the data with your knowledge in developing your responses to the questionnaires. Thus, we expect that you will review one or more catalogs of events, recognizing the shortcomings of the data (e.g., incompleteness of the catalogs). The data, in turn, should be combined with your general experience in the region, your knowledge of the geologic and tectonic features, similarities of the EUS with other regions, and other related information.

Throughout the questionnaires we will be asking you to associate a level of confidence to your responses. We will interpret your level of confidence to represent the degree to which you judge your knowledge, expertise, the historical data, etc., support a given response. In making this judgement we ask that you not be influenced by your level of expertise, for a given section

of the EUS, relative to the other panel members. The latter measure of relative expertise (self-weighting) is only approproate when opinions from several individuals are combined to form a consensus. We will be eliciting such self-weights as a separate part of the elicitation process. To illustrate, suppose you are responding to a question about the existence of a zone in a section of the EUS for which you feel your level of expertise (self-weight) on a scale of 0.0-1.0 is 0.8. Based on your knowledge, review of past-events, etc., if you are 95 percent sure the zone should be identified, then your level of confidence in the existance of the zone is 0.95, not 0.95 x 0.8 = 0.76. [If you assign confidence of 0.76 to the zones existence, this implies that your confidence in its non-existence is 0.24, rather than 0.05].

We recognize the inherent difficulty of quantifying subjective judgement. However, substantial uncertainty is an unavoidable factor in assessing seismic hazard in the EUS. Until more data becomes available expert opinion about seismicity is an important source of information. It is widely accepted that subjective probability (i.e., in our terminology, level of confidence) is the uniquely appropriate means of quantifying uncertainty. Thus, eliciting your level of confidence is an attempt to assist you in sharpening and quantifying your opinions as well as to express your uncertainty. We encourage you to be as unbiased and complete as possible in responding to the questionnaire.

Although the goal is to describe the seismicity of the entire EUS, it is recognized that some of you will not feel comfortable in responding for the entire region. However, we urge you to supply zones for all regions if possible. Large uncertainties can be reflected in the range of alternatives presented and through the level of confidence associated with a response. We want to emphasize that, in addition to assessing the best estimate hazard curve and associated uncertainty for each expert, the intent of the project is not to obtain a consensus but to present the diversity of opinion among different experts. Therefore, we urge you to express your own knowledge and beliefs in your responses. Specifically, do not be reluctant to express unconventional and/or non-classical viewpoints.

If you feel that you cannot respond to our questions for certain regions of the EUS, this is acceptable. In that case respond only to the portion of the EUS for which you are knowledgeable. However, whatever portion of the EUS you respond to, we urge you to answer all questions.

2. SOURCE ZONE CONFIGURATION

2.1 Introduction

In this part of the elicitation process we are concerned with the specification of various seismic source zones. A zone is a region which has homogeneous seismic characterictistics in terms of rate of activity, magnitude disdtribution and upper magnitude cut-off. The intent of this section is to obtain the geographic boundaries of the major seismic zones and local tectonic features, e.g., faults, which should be considered in a seismic hazard analysis. The region to be considered is the Eastern United States and Southeastern Canada extending west to the Rocky Mountain front or roughly 104°W.

We will be asking you to draw a base map of the seismic source zones for the Eastern United States and Southern Canada on one of the maps provided . The base map should:

- o Identify all potential seismioc zource zones
- o Describe your "best estimate" of the boundaries of the zones.

It is recognized that you may have alternative views about the zonation other than your initial base map. Specifically, you may be uncertain about:

- o the existence/non-existence of an individual zone or cluster of zones, i.e., should/should not an individual zone or cluster of zones be treated as a source separate from the area surrounding it,
- o the boundary shape of an individual zone or boundaries of a cluster of adjacent zones.

Thus, we will be asking you questions which will allow you to express such uncertainty.

We have provided several maps which can be used to indicate alternative source zone configurations. Please do not return your responses on any other working maps or even copies of the maps provided to you. In processing your responses, these maps will be digitized and therefore need to be all the same. If you need more maps, please do not hesitate to request them from us.

To assist you in interpreting and answering the questions for this part of the elicitation, we have included an illustration of the type of response we hope to derive from the questions in this section of the questionnaire. Please recognize that this illustration is not intended to reflect reality but only to illustrate the desired format for your responses. (In fact, the illustration was purposely done by a non-seismologist).

In the illustration, Figure A1 describes the base map, in response to Question 1-1. Each zone has been indexed. Indexing zones is necessary for later identification when one describes alternative configurations in response to later questions. In this illustration 15 zones were identified. Most of the

zones are aras, except Zone 2 which is a line source. Table A1 illustrates the response to Question 1-2 on uncertainty in the existence of one or more zones identified on the base map. The zones identified in Table A1 are those for which the respondent was not sure about their existence, i.e., the need to identify a separate source zone different from the surrounding area. Two pieces of information are provided for each zone identified in Table A1:

- o the respondent's level of confidence that a zone does exist

- o if the zone is considered non-existent, the region must become part of another zone; this zone must be identified.

In the illustration, Zones 2, 3, 4, 5, 12, and 14 were considered potentially non-existent. The respondent's confidence in Zone 2 existing is 0.40 and if Zone 2 does not exist then that region becomes part of Zone 1. Similarly, the respondent has confidence 0.85 that Zone 3 must be identified as a separate source zone.

Responses to Question 1-3 on potential alternative boundary shapes for an individual zone or group of zones is illustrated in Figures A2 and A3 and Table A2. In this case, Zone 3 was considered to have two potential configurations; the elliptical shape on the original map and a triangular shape drawn on Figure A2. The respondent's confidence, conditional on the zone's existence, in the elliptical shape boundary was 0.6 and in the triangular boundary was 0.4. These are entered in Table A2. Also, in the illustration, alternative configurations for Zones 11 through 15 are drawn on Figure A2 as Zones 19 through 24. Finally, zones labeled 4 and 5 in the initial map were judged to have two additional boundary shapes. These are labeled 17 and 18 in Figure A2 and Zone 25 in Figure A3. Notice that in the latter alternative, the region originally described by two zones has been described by a single zone.

Although most of the source zones identified in the illustration represent areas, there are also relevant line and point sources, such as faults, which could be active or could otherwise serve to localize seismicity. It is important that you identify such line and point sources on your maps and treat them in your responses as another zone, indexing them, consider their existence/non-existence and possibly reshaping or relocating them on your alternative maps.

2.2 Questions

1-1 Using one of the maps provided, please draw your base map of potential source zones, along with their "best estimate" configurations, for the Eastern United States. Please index each zone identified on your map.

1-2 To express an uncertainty about the possible existence of an individual zone or cluster of zones, please record, by index number, in a table similar to Table A1, any regions which you are not certain should be identified as a zone. Indicate your level of confidence in its being a zone and indicate what zone that region will be part of if the zone does not exist.

1-3 To indicate possible alternative boundaries for an individual zone or cluster of adjacent zones, please isolate the zones you would like to reshape; provide as many alternative boundaries, on one or more of the maps provided, as you feel is necessary; and, in a table similar to Table 2, list the alternatives and give us an expression of your confidence (relative to the other alternative shapes for that zone or zones) in each alternative boundary shape.

As indicated in the Introduction we will provide, if you desire, a description of historical seismic activity relevant to your source zone configurations which you can use as a data base for responding to the questions on seismicity in the second stage of the elicitation process.

1-4 Do you desire to have us provide you a description of historical seismic activity in the EUS?

Yes ______ No ______

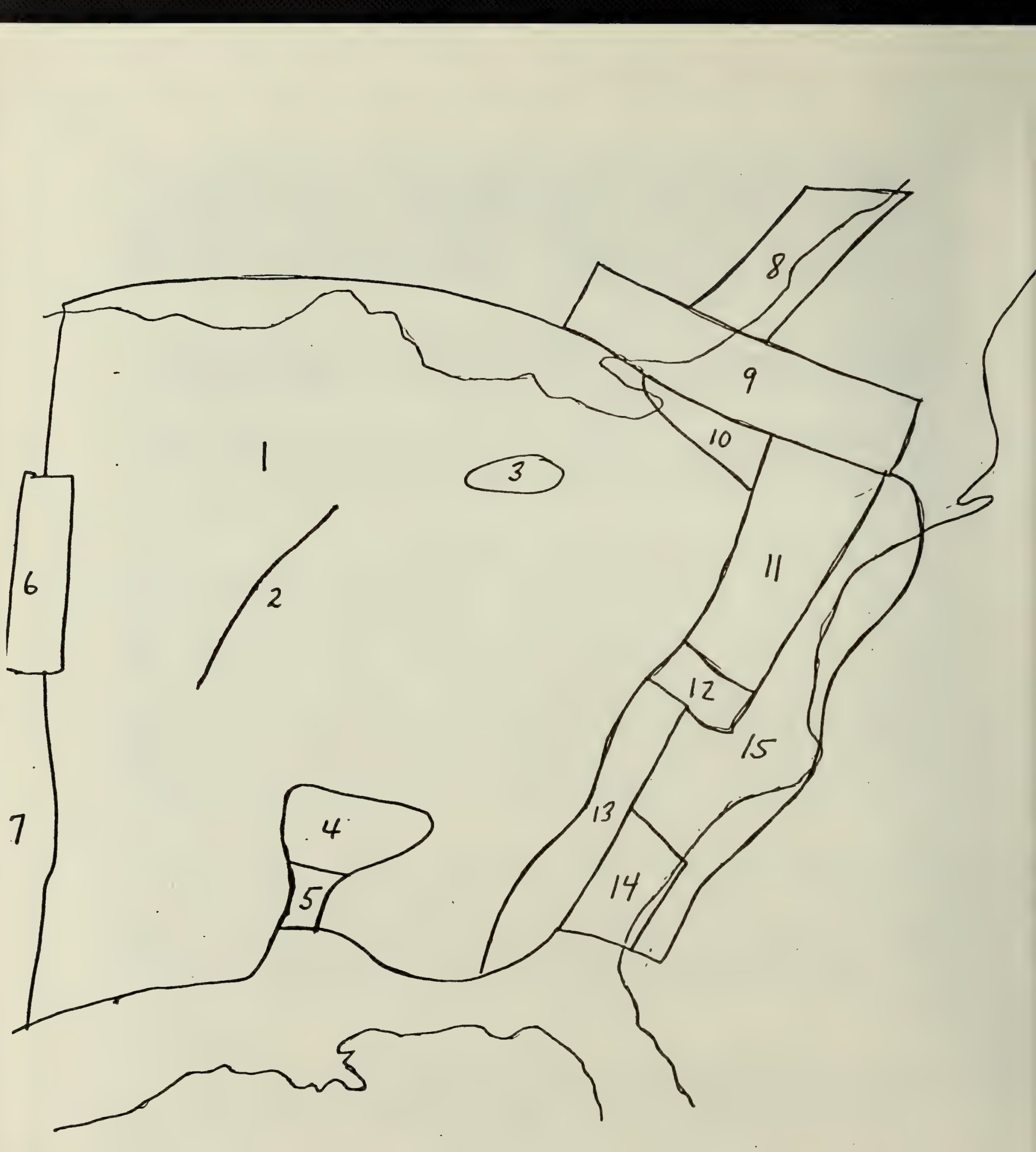

Figure A1. "Best Estimate" Source Zone Configurations

Table A1. Existence of Selected Zones

Zone Index	Level of Confidence In Existence	Non-Existent Zone Becomes Part of Zone Number
3	0.85	1
4 and 5	0.98	1
12	0.70	11
14	0.80	15

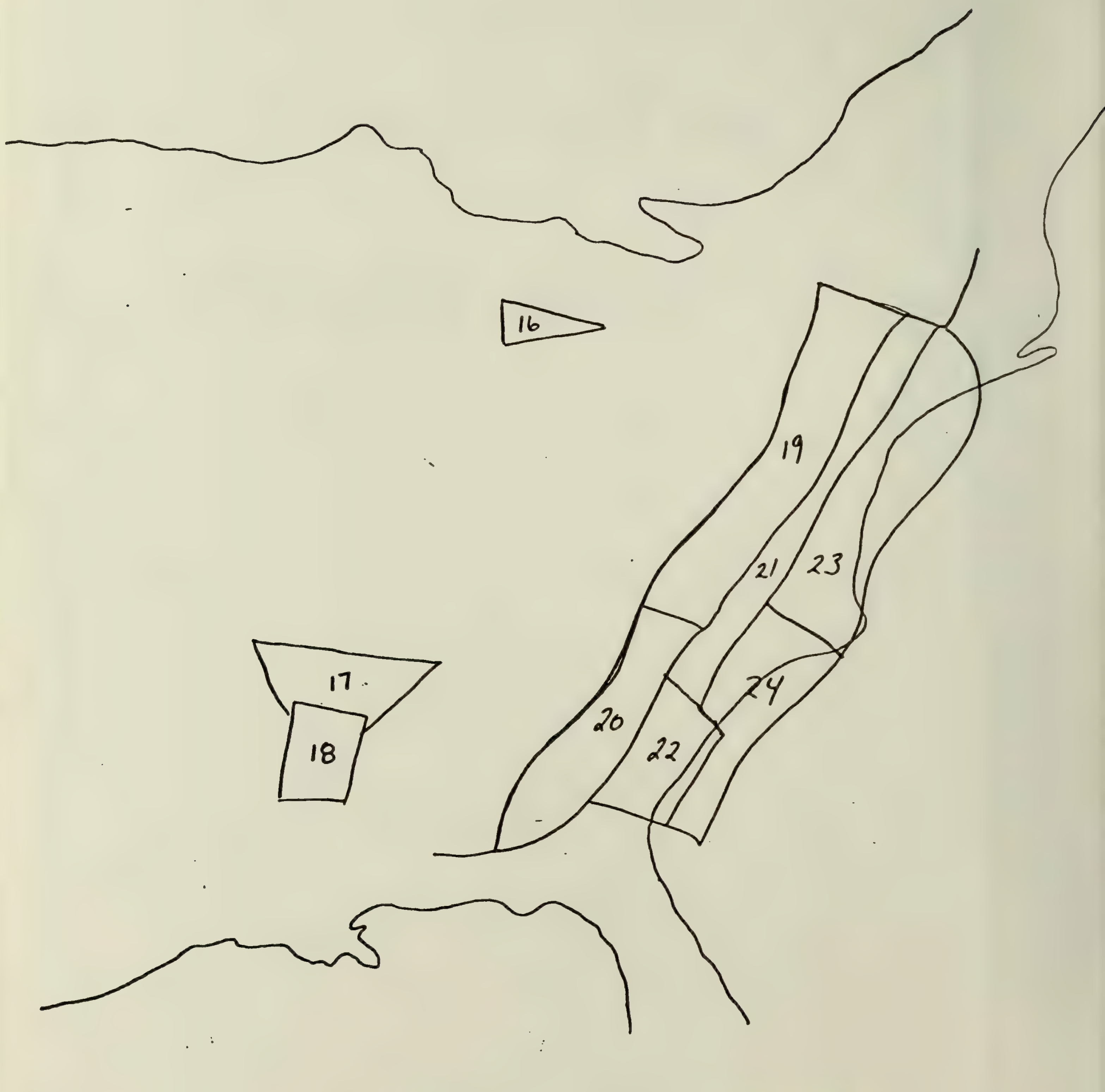

Figure A2. Alternative Source Zone Configurations

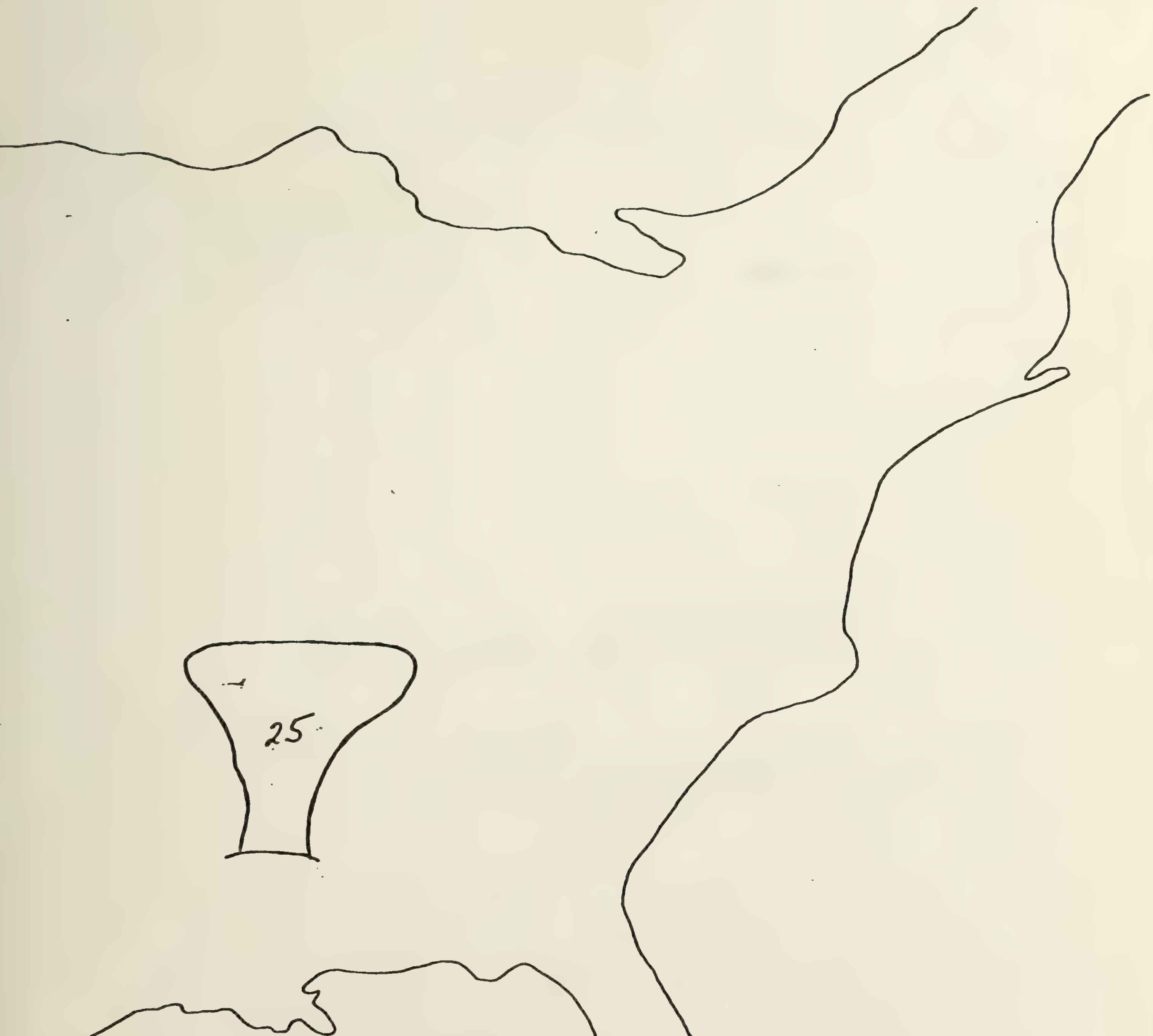

Figure A3. Alternative Source Zone Configurations

Table A2. Confidence for Alternative Boundaries

Zone Index	Level of Confidence(1) In Boundary Shape
3	0.6
16	0.4
4, 5	0.7
17, 18	0.15
25	0.15
11, 12, 13, 14, 15	0.7
19, 20, 21, 22, 23, 24	0.3

(1) Notice that for any specific region, the sum of the levels of confidence over alternative boundary shapes should be 1.0.

SECOND QUESTIONNAIRE - SEISMICITY PARAMETERS (Q2)

SECOND QUESTIONNAIRE - SEISMICITY PARAMETERS (Q2)

1. EASTERN UNITED STATES SEISMICITY

1.0 Introduction

As part of the project to develop a seismic hazard characterization of the EUS, this questionnaire is designed to elicit your opinions about the seismicity of the source zones you identified in Questionnaire 1. For each of the zones[1] identified in your zonations of the EUS we will ask questions about:

- o The largest earthquake, i.e., upper magnitude cutoff
- o The expected frequency or occurrence rate of earthquakes
- o The magnitude-recurrence relation

We are returning to you digitized versions of the maps you developed for Questionnaire 1 as well as historical seismic data, if you requested this information.

In responding to questions about seismicity we expect that you will use one or more catalogues of historical events, either those of your own choosing or the catalogue we have supplied at your request. When using the catalogues to assess the future seismicity in the EUS it is important that you consider the validity and quality of the data as well as some potential shortcomings in using the recorded events to form your opinions. One issue you should consider is the potential incompleteness of the data. The completeness of a catalogue will depend on several factors, e.g., the length of recorded history, the population density and distribution during past events. Completeness is likely to vary between catalogues as well as between regions within a catalogue. It would be appropriate for you to correct for incompleteness when using the data to form your opinions. You should also be aware of potential inaccuracies in the location and size of the past events. In addition, aftershocks are a potential source of uncertainty when using historical data. Since our analysis is based on assuming earthquakes occur as a Poisson process, one might question the inclusion of aftershocks when using the data to assess seismicity. How to treat aftershocks is left to your discretion. Aftershocks have not been culled from the data in the catalogue we provided.

The extent to which you rely on the historical data to form opinions about the future seismicity of the EUS should be based on your judgements of the data. This may be based on your knowledge of the geologic and tectonic features of the area, similarities with other regions, theoretical considerations, results of studies available to you, and any other information you feel is related to the seismicity of the EUS. Thus, your responses to questions about seismicity should reflect your assimilation of the data with your knowledge and experiences relevant to the seismicity of the EUS and your evaluation of the historical record of seismicity in the various zones.

(1) In using the generic term zone in this questionnaire, we are referring to all tectonic features (e.g., areas, faults) identified on your maps as potential sources of earthquakes.

For each seismic parameter used to characterize seismicity within a zone, e.g., the expected frequency of earthquakes, we will ask you to give your best estimate of the value of the parameter. In addition, we will ask you to give an interval of values for each parameter to which you associate a high degree of confidence. As discussed in the Introduction in Questionnaire 1, confidence is considered to reflect your state of knowledge regarding the seismic parameter conditional on the historical data, your knowledge about and experiences with the geologic and tectonic conditions in the EUS, and any other information relevant to the seismicity in the region. We do not ask you to associate a specific level of confidence with the interval because of the difficulty we expect you would have in distinguishing between similar confidence levels, e.g., distinguishing between 90 and 95 percent levels of confidence. However, in our analysis we will model your state of knowledge about a parameter by assigning a probability distribution to each seismic parameter. Your best estimate and confidence bounds will be used to estimate the parameters of the probability distribution. In this context we will associate a specific level (e.g., 95 percent) of confidence with your interval. This interval should represent a set of values, in which you are highly confident that it includes the true value of the parameter. The width of the interval should reflect the uncertainties you have about the seismicity within a zone.

We would like to emphasize that it is important, for the success of this project, that you respond to <u>all</u> questions for each of the zones identified in the first questionnaire. Thus, even if you are uncertain about one or more seismic property for a zone, we encourage you to express an opinion. Your uncertainty should be reflected in your responses to questions involving a statement of confidence. Moreover, even if you believe some seismic features (e.g., the magnitude-recurrence relation model) are similar for all zones, you should consider each zone individually in making your responses. For example, even if your best estimate of the slope of a linear magnitude-recurrence relation is the same for all zones, your uncertainty about this parameter may vary from zone to zone; one reason for this is that the quality and amount of historical data varies from zone to zone. This variation in uncertainty should be reflected in varying confidence bounds for the slope from zone to zone.

To help you understand the reasons for the questions we pose in this questionnaire as well as why we emphasize the need for you to respond to all questions, we will outline how the three items addressed in this questionnaire (frequency of earthquakes, upper magnitude cutoff, magnitude- recurrence relation) enter into the hazard analyses.

For this project, seismic hazard at a site is defined as the probability P(A a) that the peak acceleration A at the site exceeds the value a. That is, P(A a) is the probability that at least one earthquake occurs for which the peak acceleration at the site exceeds a. This probability is experessed per unit time, e.g., 2.8 X 10^{-3} per year. The seismic hazard curve is frequently described by a plot of the logarithm of P(A a) versus a. (See Figure 1.1 in Questionnaire 1.) The peak acceleration at a site is assumed to be functionally related to earthquake magnitude and source-to-site distance.

Hence, the hazard $P(A > a)$ depends on the distribution of peak acceleration conditional on magnitude and source-to-site distance, as well as the distribution of magnitudes, integrated over relevant source zones. The upper magnitude cutoff is the parameter of the distribution of magnitudes which defines the largest possible earthquake for each zone. The expected frequency of earthquakes and the magnitude-recurrence relation are jointly used to describe the frequency of magnitudes between the specified minimum level M_O and the upper magnitude cutoff M_U. Our hazard analysis methodology, similar to that used in the previous study, uses your inputs about the seismicity within a zone to estimate the expected frequency of earthquakes for a finite set of magnitude intervals spanning the range between M_O and M_U. Assuming a Poisson model for the occurrence of earthquakes in each zone, we can integrate over the relevant zones to assess the seismic hazard at a site, conditional on the values of the seismic parameters.

We will combine your best estimate and interval estimates of the seismic parameters, along with your responses to the questions in Section 4, to specify a joint probability distribution for the seismic parameters. This distribution will be used to assess a best estimate hazard curve and bounds for the hazard curve which represent your uncertainties in the seismicity of the EUS. Details about the appropriate probability distributions and about how we will interpret your inputs to estimate these probability distributions are discussed in the respective sections of the questionnaire. A discussion of the precise method for assessing the seismic hazard at a site and propagating the uncertainties through the analysis are too complex to present in this introduction. Details for the complete seismic hazard analysis, including the procedures for propagating uncertainty through the analysis, will be presented for your review at the general meeting of the panel during the third stage of the elicitation process.

2. UPPER MAGNITUDE CUTOFF

2.1 Introduction

An important parameter of the magnitude distribution is the upper limit of the range of magnitude values. This limit corresponds to the largest magnitude that will occur given the current geologic and tectonic conditions within a zone. This part of the questionnaire is concerned with eliciting your opinions about this limiting magnitude value for each zone identified in your seismic zonation of the EUS.

When one considers the magnitude of the largest event that can occur in a source zone, one might imagine that this will depend on the time length to be considered. For example, if one considers periods of 150 years and 1,000 years, one might expect the magnitude of the largest event to be different for the two time periods. In fact, if one were able to record the magnitudes of all earthquakes within a source zone over two such time intervals it would not be unusual for the largest event in 150 years to be different than the largest event in 1,000 years. This would be true even if the tectonic and geologic conditions of the region remained constant over time, since the magnitude of the largest event in T years, M_T, is a random variable. Thus, values observed over the 2 time periods would be realizations from two distributions of values. It is true that the probability distributions of these random variables will depend on T. However, assuming that the seismic, tectonic, and geologic conditions of the region remain constant over time, the range of values, specifically the lower and upper limits of the distributions, will be the same for both distributions. Conceptually, the relationship between the distributions of the largest earthquake in 150, 500, and 1,000 years is shown in Figure 2.1. Notice that all three distributions have a common upper limit, denoted M_U. However, the probability that the largest earthquake has a magnitude close to M_U decreases as the time period T decreases. This common upper limit is the parameter of interest in this section of the questionnaire.

The assumption that the range of values of the distribution of magnitudes is independent of time suggests, perhaps, that the value of the upper limit must include magnitudes of events which may occur as a result of potential long term changes in geologic and tectonic conditions. This is not the case for this project. In your responses, you should not consider the consequences of a change in tectonic conditions, for example, a change of the Atlantic margin to a subduction zone. The purpose of this project is to consider the seismicity of the region as it exists today and can be expected to exist in the near geological future.

The tectonic and seismic conditions currently existing within a zone will limit the magnitude of an earthquake, should an earthquake occur. This limiting value of magnitude, determined by the physical conditions within a zone, is the upper limit of the distribution of magnitudes. We refer to this parameter as the upper magnitude cutoff.

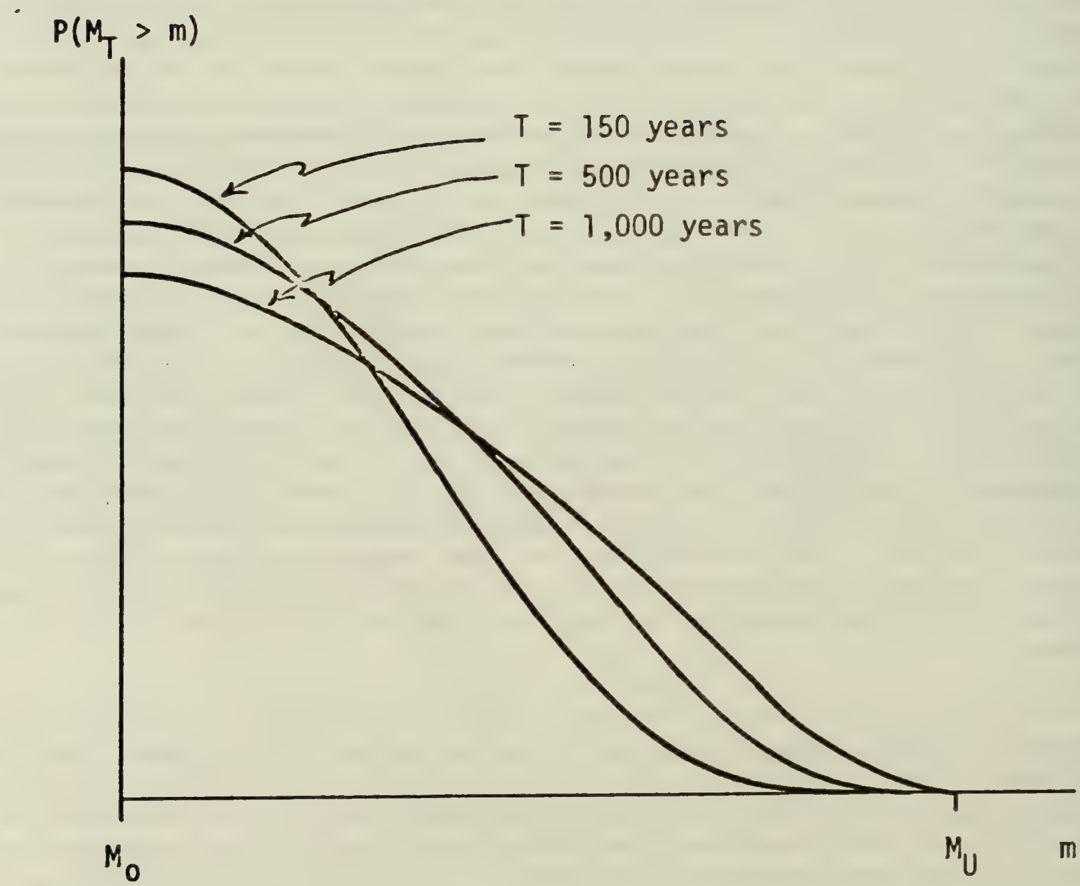

Figure 2.1 Probability that the Magnitude of the Largest Earthquake, M_T, in T Years Exceeds m.

Definition:

Upper Magnitude Cutoff, M_U - the upper limit for the distribution of earthquake magnitude within a zone, given the current tectonic and seismic conditions.

If the current tectonic and seismic conditions were to remain stationary and the magnitudes of all earthquakes were recorded for a long time, the collection of magnitudes would form a distribution of magnitudes, the upper limit of which is the parameter M_U. The parameter M_U should be distinguished from the random variable M_T discussed above.

An important consideration in the assessment of the upper magnitude cutoff is the saturation properties of the measurement scales presently used to describe the magnitude of an earthquake. For example, the Modified Mercali Intensity (MMI) scale has an upper value of XII. Thus, no matter what the total energy (or moment) associated with an earthquake, its magnitude, when measured in MMI, can never exceed XII. Similarly, the energy (or moment) - magnitude relationship, when magnitude is measured in M_{bLg} units, is described in Figure 2.2. Thus, when responding to questions concerning an upper magnitude cutoff, if one's response is expressed relative to observable magnitude values, the magnitude saturation value is an upper limit. On the other hand, when assessing the upper magnitude cutoff you may not want to be constrained by the saturation value. This can be done by expressing one's opinion in an alternative magnitude scale (e.g., in M_s). Alternatively, to avoid problems of changing magnitude scales (e.g., from M_s to M_{bLg}) and the uncertainty of the relation between scales, you may want to continue the linear portion of the moment-magnitude relation beyond the saturation value (indicated by the dashed line in the figure). To allow you as much flexibility as possible in expressing your views about the upper magnitude cutoff, you should feel free to consider or not consider the saturation of the measurement scale in your responses. We do ask you, however, in Question 2-2 to indicate if you are limited by a saturation value.

In Question 2-4 we ask you to specify an interval for the upper magnitude cutoff M_U to which is associated a level of confidence. This interval will be combined with your best estimate to describe your uncertainty about the value of M_U. In this description we will treat your best estimate as the most likely value (mode) and the endpoints of the interval as the limits of a triangular distribution similar to that shown in Figure 2.3. If you feel the triangular distribution does not adequately describe your uncertainty in the value of the upper magnitude cutoff, you should indicate an appropriate distribution in response to Question 2-5. Such a distribution can be expressed in terms of a density (relative frequency) function e.g., the uniform density function in Figure 2.4a, or in terms of a cumulative distribution function, e.g., the uniform distribution function in Figure 2.4b.

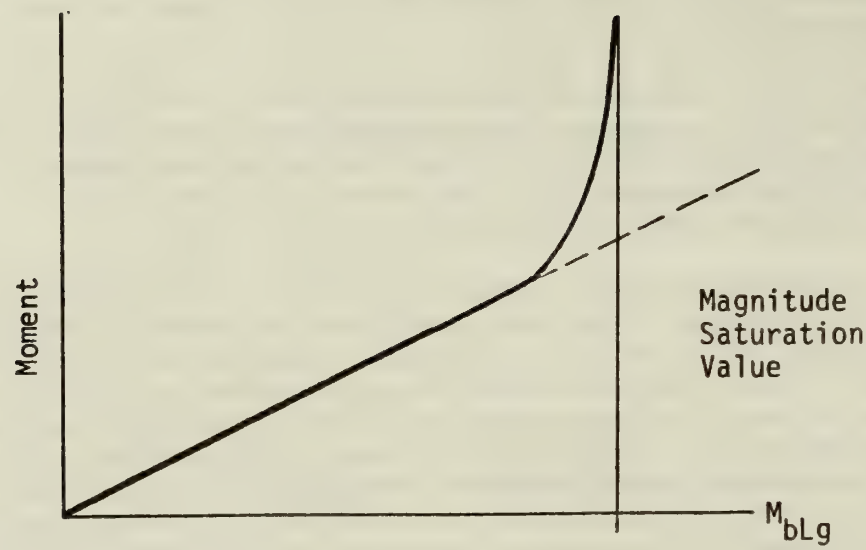

Figure 2.2 Moment - Magnitude Relationship

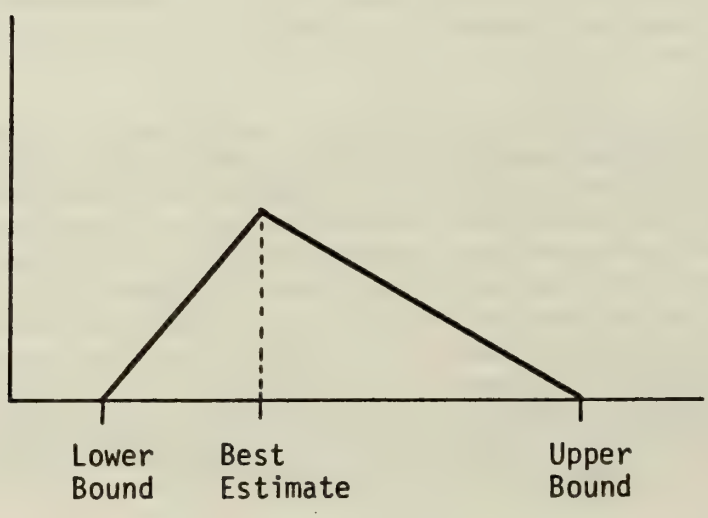

Figure 2.3 Triangular Density Function

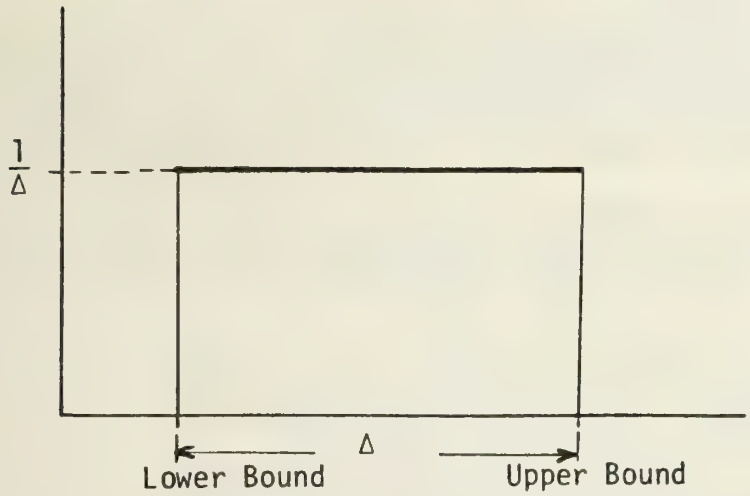

Figure 2.4a Uniform Density Function

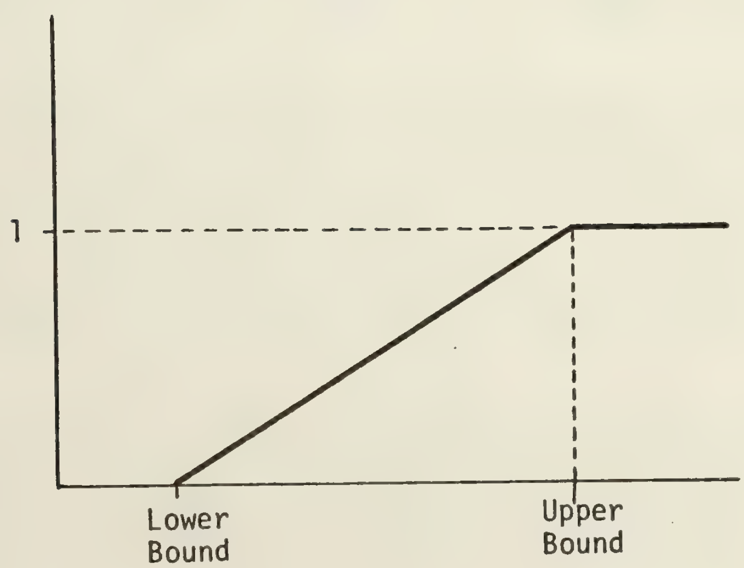

Figure 2.4b Uniform Distribution Function

2.2 Questions

For each of the seismic source zones identified on your maps of the zonation of the EUS.

2-1 What scale of measurement (e.g., MMI, M_{bLg}, etc.) for earthquake magnitude will you use for your responses to questions about the upper magnitude cutoff? (Note: It is not necessary to use the same scale for all zones; indicate, separately, the scale you are using for each zone.)

2-2 Will you, in your responses concerning the upper magnitude cutoff, be constrained by the saturation value (e.g., XII on the MMI scale) on your chosen scale of measurement? If so, what is the saturation value?

2-3 Given the current tectonic and seismic conditions for each zone, give your best estimate (most likely value) for the upper magnitude cutoff M_U for the distribution of magnitudes for the zone.

2-4 Give a lower bound M_{UL} and an upper bound M_{UU} for the value of the upper magnitude cutoff such that the range (M_{UL}, M_{UU}) is a reflection of your confidence in estimating the upper magnitude cutoff. As indicated in Fig. 2.2, the interval (M_{UL}, M_{UU}) will be treated as a 100% confidence interval for M_U.

2-5 Does the triangular distribution adequately describe your uncertainty in the value of the upper magnitude value? If not, please indicate an appropriate distribution.

3. EARTHQUAKE OCCURRENCES

3.1 Introduction

In this part of the questionnaire we elicit your opinions about the occurrence of earthquakes with magnitudes between a minimum magnitude M_0 and the upper magnitude cutoff in each of the source zones identified on your maps of the zonation of the EUS. For this project, the minimum magnitude, in MMI units, is M_0 = IV and, in M_{bLg} units, is $M_0 = 3.75$. To elicit your opinions we ask you to respond to questions about:

1. The expected frequency (occurrence rate) of earthquakes with magnitude equal to or greater than M_0 within a zone.

2. The magnitude-recurrence relation within a zone.

We recognize that by requesting your opinions about the expected frequency and the magnitude-recurrence relation, we are potentially eliciting redundant information. Specifically, for a specific time period, if the magnitude-recurrence relation is applicable at M_0 then it can be used to estimate the expected frequency of earthquakes with magnitude equal to or greater than M_0. However, since the magnitude-recurrence model is usually derived from historical data, data which might be incomplete for magnitudes close to M_0, one might believe that the magnitude-recurrence model does not hold for all magnitudes. In this case, the two sets of questions are not redundant but provide needed inputs into the seismic hazard analysis. We further address the issue of the range of applicability of the magnitude-recurrence relation in Section 3.4.

By asking both questions, it provides you an opportunity to estimate the expected frequency by viewing the historical data from more than one perspective. For example, an estimate of the expected frequency can be based on only the number of earthquakes occurring over a period of time. On the other hand, the estimate from the magnitude-recurrence relation is influenced by the model used to fit the historical data. Thus, we have estimates of similar parameters based on different methods of analyzing the historical data. We recognize, of course, that you may choose to use entirely different procedures as a basis for your responses.

In any case, we request that you respond to questions about both expected frequency and the magnitude-recurrence relation. In doing such we hope that you will consider both questions separately and not derive the obvious response of one from the other. This permits us to treat your responses to both sets of questions equally in the seismic hazard analysis.

In responding to questions regarding the occurrences of earthquakes we expect you will use historical data on the seismic activity in the EUS, either your own data or the catalogue of historical events we have provided. Of course, when using this data to subjectively assess future seismicity in the EUS it is important that you use your judgment as to the validity, quality, and completeness of the data in determining how much you will rely on the data to

form your opinions. If you are using the catalogue that we provided at your request, it should be recognized that no corrections for completeness have been performed on it nor have aftershocks been culled from the data. The analysis of the completeness of the catalogue and the use of aftershocks has been left to your discretion. Your judgments of the data may be based on geologic and tectonic considerations, similarities with other regions, theoretical considerations, results of your own studies or other studies available to you, or any other information which you feel influences the seismicity in the EUS.

We will ask you to provide your best estimate of the seismicity parameters and to express your uncertainty about each parameter by specifying an interval for the value of the parameter to which you associate a high degree of confidence. When modeling your uncertainty about the parameters in this section, the confidence interval is interpreted to be the set of values for which your personal confidence is 0.95 (i.e., a 95 percent level of confidence) that the true value lies within that range. As discussed earlier, the level of confidence reflects the degree to which you judge the data, tectonic and geologic conditions, etc., support a given response.

In the seismic hazard analysis, rather than imposing a parameteric model on the magnitude distribution, we take a nonparametric approach and base our analysis on the occurrence rate for each subinterval in a finite partition of the magnitude range (M_o,M_U). Your best estimates and confidence bounds for the seismic parameters are transformed into a best estimate and confidence bounds for the magnitude-recurrence relation using the functional form (e.g., linear) of the relation you supply. The best estimate and confidence bounds for the magnitude-recurrence relation will be used to specify the means, variances and covariances of the occurrence rates for the subintervals. These will, in turn, be used to determine the parameters of the joint distribution of the occurrence rates, which is modeled as a multivariate gamma distribution.

3.2 Magnitude Scale

When analyzing your responses to questions about earthquake occurrences it is important that the magnitude scale you use in making your responses be clearly identified. You are free to use whatever scale you feel permits you to best express your opinions about seismicity within a zone. The same scale need not be used for all zones. In Question 3-1 we ask you to identify the magnitude scales you will use in your responses about earthquake occurrences.

The seismic hazard analysis will be based on magnitudes in either the MMI or M_{bLg} scales. Thus, if you use any other magnitude scale it will be necessary to transform the responses in your chosen scale to statements on either the MMI or M_{bLg} scale. To make this transformation we will need to know the relationship between the magnitude scales you will be using and either MMI or M_{bLg}. To ensure the integrity of your answers, we ask you to describe this relation.

Also, the hazard analysis will involve several ground motion models, some of which involve intensities and some involving magnitudes. Thus, it is necessary for us to move between the epicentral intensity $(MMI)_E$ expressed in the MMI scale and M_{bLg} scale. To do this we propose to use the relation

$$(MMI)_E = 2M_{bLg} - 3.5$$

If you do not feel that this is the best model for relating $(MMI)_E$ and M_{bLg} measurements, you can indicate such in your response to Question 3-4.

Finally, the seismic hazard analysis is based on assessing the hazard at a site in the EUS due to earthquakes with magnitudes above a minimum level. For purposes of this project, the minimum magnitude, M_o, is either $(MMI)_E$ = IV or $M_{bLg} = 3.75$. In this analysis it is assumed, from a structural standpoint, the effect on a nuclear power plant of earthquakes of magnitude below IV or 3.75 will be insignificant and hence need not be taken into consideration. If you respond to questions about seismicity in other than the MMI or M_{bLg} scales, it is important to identify the corresponding minimum level.

Questions

3-1 In your responses to questions about earthquake occurrences, please list all the magnitude scales you will use. Note: It is not necessary to use the same scale for all zones.

For any magnitude scale other than MMI and M_{bLg} identified in Question 3-1, please

3-2 Describe the relationship between that scale and either the MMI or M_{bLg} scale.

3-3 Indicate the minimum magnitude, M_o, below which the effect of the earthquake will be insignificant.

When transforming between $(MMI)_E$ and M_{bLg} scale in our analysis we propose to use the relation

$$(MMI)_E = 2M_{bLg} - 3.5$$

3-4 Do you agree with this relation? If not, please indicate the relationship you believe is more appropriate.

3.3 Expected Frequency of Earthquake

An important parameter for characterizing the seismicity of a zone is the frequency with which earthquakes occur within the zone. Since a seismic hazard analysis is based on considering the effect of earthquakes having magnitudes or epicentral intensities greater than some minimum level, we are only interested in the occurrence of earthquakes with magnitude at the minimum

level or greater. The questions in this part of the questionnaire are designed to elicit information about the expected frequency of earthquakes within a zone with magnitudes at or above the minimum level.

For purposes of this project the minimum magnitude, M_0, is either $(MMI)_E$ = IV or M_{bLg} = 3.75. If you are responding to questions about magnitude in any other scale, e.g., in M_s units, there is a corresponding minimum level below which the effect of the earthquake on a nuclear power plant will be insignificant.

The expected frequency can be expressed either in terms of the rate of occurrence within a zone per year, e.g., 0.313 per year, or the number of earthquakes expected to occur in a zone within a specified period of time, e.g., 47 in 150 years. The time period is left to your discretion. The period you use may depend on the catalogue of historical data you choose and your opinion about the completeness of the data. The same time period need not be used for all zones. We are interested in assessing the seismic activity in each zone under the geologic and tectonic conditions as they exist today and can be expected to exist in the near geological future. Thus, in using the historical data one must judge, in addition to the completeness of the data, how well past seismic activity reflects activity that may occur in the future under present conditions.

Questions

For each of the seismic source zones identified on your maps of the zonation of the EUS:

3-5 What scale of measurement for earthquake magnitude will you use for your responses to questions about the expected frequency of magnitudes greater than M_0?

3-6 Give your best estimate of the expected frequency, either in terms of the mean rate per year or the expected number in T years, of earthquakes with magnitude at or above M_0 occurring within the zone. Indicate the time period T.

Note: The expected frequencies should be expressed as the rate (number) per zone, not per unit area.

3-7 Give an interval which you believe, with a high degree of confidence, represents the possible values of the expected frequency.

3.4 Magnitude Distribution

Conditional on an earthquake of magnitude M_0 or greater occurring within a zone, the magnitude of the earthquake can be any value between M_0 and M_U, the upper magnitude cutoff. Thus, given that an earthquake occurs within a zone, its magnitude is the value of a random variable drawn from a distribution of magnitudes. The purpose of this part of the questionnaire is to elicit information which characterizes this distribution.

Several methods can be used to describe the magnitude distribution. Certainly, one simple method would be to list a set of distinct magnitude values along with the frequency or relative frequency corresponding to each magnitude. However, the method most often used is based on the magnitude-recurrence relation. This is a model for the relationship between the $\log_{10} N_m(T)$ and m for magnitudes between M_o and M_U, where $N_m(T)$ is the number of earthquakes exceeding magnitude m in T years. Three such models, or magnitude-recurrence relations, are illustrated in Figure 3.1. The choice of the function , e.g., linear, quadratic, piecewise linear, as well as the values of the model parameters, e.g., a, b, c, characterize the magnitude distribution.

Another method for describing the magnitude distribution, which may be analogous to specifying a magnitude-recurrence relation, is to model the magnitude distribution in terms of a well known probability distribution, e.g., the exponential distribution. The choice of the distribution, e.g., exponential, as well as the values of the parameters of the distribution characterize the magnitude distribution. When using well known probability distributions it must be recognized that most probability distributions are defined over an infinite range, e.g., zero to infinity. Since the upper magnitude cutoff, M_U, is finite, it will be necessary to truncate the probability distribution at M_U when using such models to describe the magnitude distribution.

Although any of these methods is adequate to describe the magnitude distribution, it is most convenient for our analysis to characterize the magnitude distribution in terms of the magnitude-recurrence relation. Thus, we encourage you to respond to Questions 3-8 through 3-16 which elicit information about the magnitude distribution in terms of the magnitude-recurrence relation. However, if you feel you can better characterize the magnitude distribution using another method then please use the alternative method. In any case, it is important that the magnitude distribution be completely characterized, i.e., both functional form and parameter values, for all zones.

Questions

Questions 3-8 through 3-16 are based on characterizing the magnitude distribution in terms of a magnitude-recurrence relation. If you are using an alternative method to describe the distribution of magnitudes, skip questions 3-8 through 3-16 and go directly to Question 3-17.

3-8 What scale of measurement (e.g., MMI, M_{bLg}) for earthquake magnitude will you use for your responses to questions about the magnitude-recurrence relation?

3-9 Will you, in your responses concerning the magnitude-recurrence relation, be constrained by the saturation value on your chosen scale of measurement? If so, what is the saturation value?

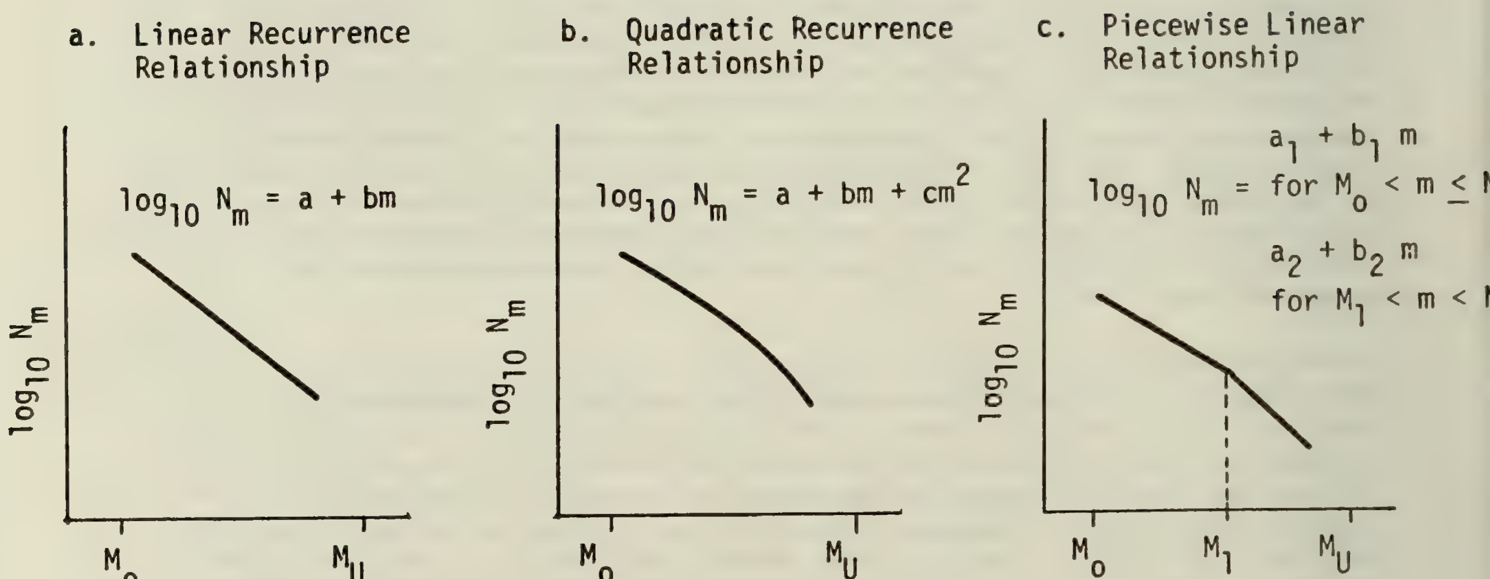

Figure 3.1 Magnitude-Recurrence Relations

In using the magnitude-recurrence relation to characterize the magnitude distribution it must be recognized that the model is an empirical relation based on historical data collected over T years. Since the entire magnitude range may not be represented in the historical data, the model derived from the data may not be applicable for all magnitudes between the minimum magnitude M_o and your maximal upper magnitude cutoff M_{UU}. We ask you to identify the range of magnitudes, denoted M_{LB}, M_{UB}, in Question 3-14. This range may vary from zone to zone.

It is necessary for the seismic hazard analyses, however, to characterize the magnitude distribution for all magnitudes including the magnitudes between M_o and M_{LB} and between M_{UB} and M_{UU}. Thus, it is necessary to extrapolate the magnitude-recurrence model beyond the range (M_{LB}, M_{UB}). You can indicate how this should be done by responding to questions 3-10 and 3-11. If you do not suggest a method we will extrapolate the magnitude-recurrence relation beyond M_{LB} and M_{UB} by a method based on assuring a continuous derivative at M_{LB} and M_{UB}, a zero derivative at M_U and a value at M_o, on the N_m scale, equal to the expected frequency of earthquakes with magnitude equal to or greater than M_o, the minimum magnitude. A graphical illustration, assuming a linear magnitude-recurrence relation, is given in Figure 3.2. Note, the vertical scale in Figure 3.2(a) is N_m rather than $\log_{10}N_m(T)$ and $\log_{10}N_m(T)$ in Figure 3.2(b). For each of the seismic source zones identified on your maps of the zonation of the EUS

3-10 Indicate the magnitude-recurrence model (e.g., linear, a + bm; quadratic, a + bm + cm^2) which, in your opinion, best represents the seismicity of the zone.

Notes: a. The same model need not be used for all zones.
b. If a piecewise model is chosen, part of the model is the specification of the "change points" e.g., M_1 in Figure 3.1c.

3-11 For the model chosen in Question 3-10 give your best estimate of the value of the parameters of the model (e.g., values of a, b, c).

3-12 Specify the time length, T, on which your estimates of the parameters identified in Question 3-11 are based.

3-13 Give an interval which you believe, with a high degree of confidence, represents the possible values for each parameter identified in your response to Question 3-11.

3-14 Specify the range of magnitude values, denoted (M_{LB}, M_{UB}), for which the magnitude-recurrence relation identified in Questions 3-10 and 3-11 is applicable.

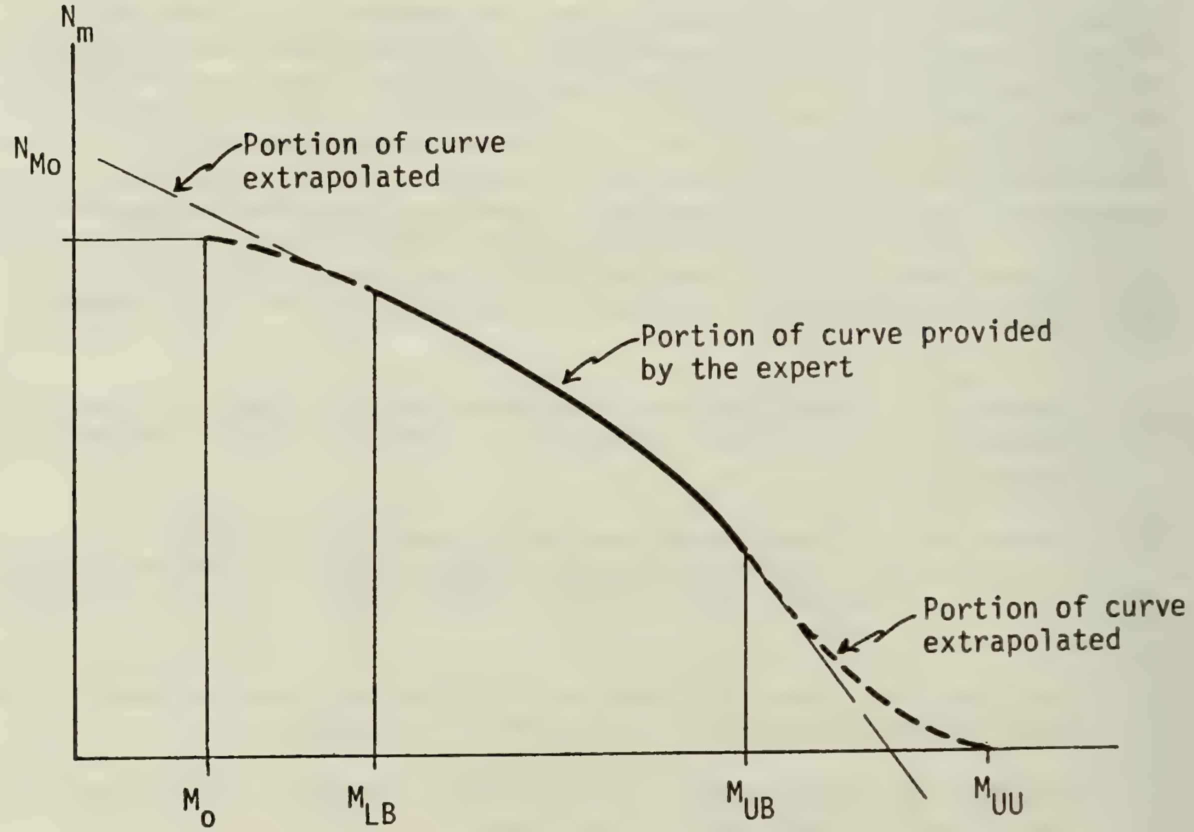

Figure 3.2(a) Extrapolation of the Magnitude-Recurrence Relation in the Number of Event versus Magnitude Space.

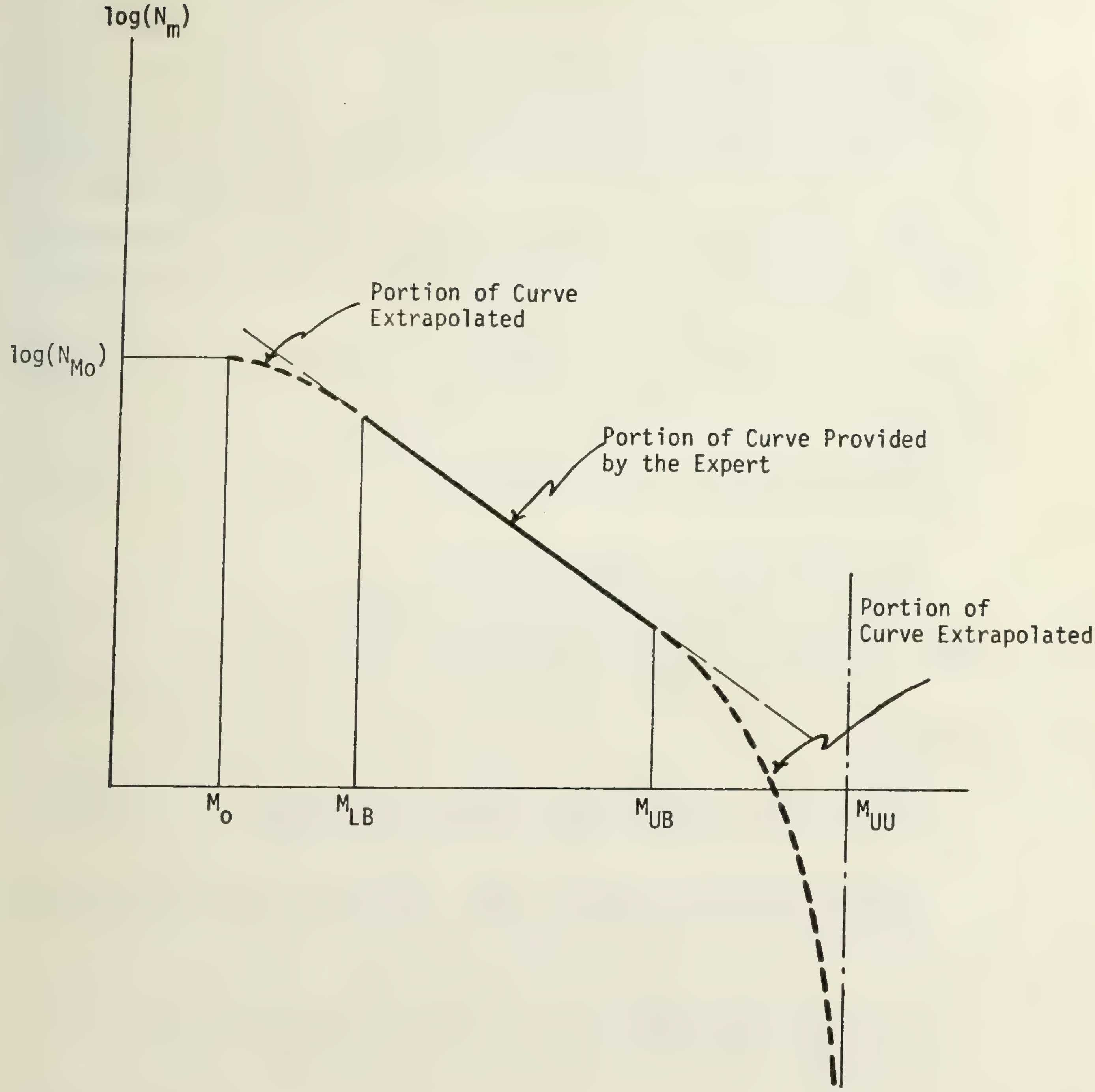

Figure 3.2(b) Extrapolation of the Magnitude-Recurrence Relation in the Logarithm of Number of Event versus Magnitude Space

If the range (M_{LB}, M_{UB}) does not coincide with the interval (M_o, M_{UU}) for some zones, it is necessary to extrapolate the magnitude-recurrence curve beyond (M_{LB}, M_{UB}) so that the frequency of earthquakes can be assessed for all magnitudes from the minimum magnitude M_o to the maximal upper magnitude cutoff M_{UU}. Extrapolation of this curve in either direction is a matter of subjective opinion. We have suggested one method for extrapolating. However, you may prefer to suggest an alternative procedure. In that case our method of extrapolation would not be applied when we analyze your inputs. Of course, when extrapolating, two restrictions on the extrapolation procedure must be recognized. Specifically, the value of N_m at $m = M_o$, the minimum magnitude, should equal the expected frequency of earthquakes with magnitudes equal to or greater than M_o and the value of N_m at M_U, the upper magnitude cutoff, should be zero. To indicate your method of extrapolation, please respond to Questions 3-15 and 3-16.

If the range (M_{LB}, M_{UB}) does not coincide with the interval (M_o, M_{UU}) for any zone and you have a method of extrapolation you feel is appropriate, please

3-15 Indicate how the magnitude-recurrence curve should be extended to magnitudes in the interval (M_o, M_{LB}).

3-16 Indicate how the magnitude-recurrence curve should be extended to magnitudes in the interval (M_{UB}, M_{UU}).

<u>If you have responded to Questions 3-8 through 3-16 for all source zones, please skip the remaining questions in this section.</u>

If you can better describe the magnitude distribution using another method (e.g., by a discrete or well known continuous probability distribution), please do so in the context of Questions 3-17 through 3-19.

3-17 What scale of measurement (e.g., MMI, M_{bLg}) for earthquake magnitude will you use in describing the probability distribution of magnitudes?

3-18 For each of the seismic source zones identified on your maps of the zonation of the EUS, specify a model for the probability distribution of magnitudes for that zone. Include in your specification your best estimate of any parameters in the model.

3-19 Give an interval which you believe, with a high degree of confidence, represents the possible values for any parameters identified in your response to Question 3-18.

4. EARTHQUAKE OCCURRENCE IN T YEARS

4.1 Introduction

As discussed in Section 2.1, the magnitude M_T of the largest earthquake in T years is a random variable. the probability distribution of this random variable is a function of earthquake frequency and magnitude distribution. Thus, your opinions about the probability distribution of the largest earthquake in T years reflect your opinions about the distribution of earthquake magnitudes.

In eliciting your opinions about the probability distribution of M_T we recognize that we are gathering more information than is absolutely necessary to analyze the seismic hazard at a site. However, use of redundant information increases the precision of our estimates and gives you the opportunity to assess seismicity from more than one perspective. We plan to develop the seismic hazard at a site based on (i) your responses to the questions in Sections 2 and 3, and (ii) your responses to Sections 2 and 3 combined with your responses to the questions in this section. This will give us an opportunity to share with you, when we discuss the output of the hazard analysis, the consequences of your assessing the seismicity of the EUS from alternative perspectives.

Since the probability distribution of M_T is related to the seismic parameters discussed in Sections 2 and 3 it would be possible to derive responses to the questions in this section directly from your responses in the preceeding sections. We prefer you did not do this but again use the historical data, the tectonic and geologic conditions of the EUS, and other relevant information to develop your opinions about the probability distribution of M_T.

To gather information about the distribution of the magnitude of the largest earthquake we consider two time periods, T = 150 years, because it represents approximately the length of recorded history in some sections of the EUS, and T = 1,000 years, because it represents a somewhat extended length of time.

As discussed previously, the distribution of M_T depends on the seismic parameters identified in Sections 2 and 3. A critical parameter is the largest magnitude possible, i.e., the upper magnitude cutoff M_U. In Section 2 we elicited your best estimate as well as an interval (M_{UL}, M_{UU}) for the upper magnitude cutoff. Since it would be impossible for you to respond to the questions in this section for all values of M_U in the range (M_{UL}, M_{UU}), we ask you to respond conditional on your best estimate, denoted M_U in the questions. Also, since your responses are conditional on M_U, you should respond to the questions in this section in the same scale of measurement as M_U.

4.2 Questions

Please respond to Questions 4-1 or 4-2 or both, and 4-3.

For each of the seismic source zones identified on your maps of the zonation of the EUS:

For T = 150 years and T = 1,000 years.

4-1 Give an estimate of the probability that the magnitude M_T of the largest earthquake in T years equals or exceeds m, conditional on your best estimate M_U of the upper magnitude cutoff, i.e., estimate

$$P\left\{M_T \geq m \mid \hat{M}_U\right\}$$

for (a) $m = \hat{M}_U - 1$, (b) $m = \frac{M_o + \hat{M}_U}{2}$, and (c) $m = M_o + 1$

4-2 Give an estimate of the median $M_T(.5)$ for the magnitude of the largest earthquake in T years, conditional on M_U. That is, estimate the value $M_T(.5)$ such that

$$P\left[M_T \geq \hat{M}_T(.5) \mid M_U\right] = P\left[M_T \leq M_T(.5) \mid \hat{M}_U\right] = 0.5$$

Information about earthquake frequency is also reflected in statements about the number of earthquakes with magnitudes exceeding a specific value. This is addressed in the next question.

4-3 Give an estimate of the expected value of the number of earthquakes of magnitude m or greater in T years, $N_m(T)$, conditional on your best estimate $\hat{M}_U$, for

(a) $m = \hat{M}_U - 1$, (b) $m = \frac{M_o + \hat{M}_U}{2}$, and (c) $m_o = M + 1$.

5. DEPTH OF EARTHQUAKES

5.1 Introduction

As described by attenuation models, the hazard at a site depends on the magnitude of an earthquake as well as the distance of the site from the earthquake source. The source-to-site distance, for some models, is a function of the surface distance of the site from a source as well as the depth of the hypocenter at the source. Thus for some models, in general, the deeper the expected depth of an earthquake, the greater the correction in the surface distance in the attenuation. In this section we elicit your opinions about the expected depth of an earthquake within each zone.

5.2 Questions

For each of the seismic source zones identified on your maps of the zonation of the EUS:

5-1 Which of the following best describes the distribution of depths at which earthquakes will occur within the zone. Earthquakes within the zone will occur:

- a. at approximately the same depth throughout the entire zone
- b. at only a small set of depths
- c. within a "continuous" range of depths.

5-2 Give your best estimate of either

- a. the single depth value
- b. the set of depths and the percentage of activity attributable to each
- c. the range of depths and a probability distribution describing the relative activity at depths throughout the range.

If your response to Question 5-1 is either b or c,

5-3 Do you believe that the depth at which an earthquake will occur within the zone will depend on the magnitude? If yes, what function best describes the relation between depth D and magnitude M (e.g., linear, $D = a + bM$; power function, $D = aM^b$)?

THIRD QUESTIONNAIRE - WEIGHTS (Q3)

Lawrence Livermore National Laborator

NUCLEAR SYSTEMS SAFETY PROGRAM

July 20, 1983
EG-83-62/1034u

Professor Gilbert A. Bollinger
604 Newman Lane
Blacksburg, Virginia 24060

SUBJECT: "Self Rating" Questionnaire
EUS Seismicity Modeling Panel
Seismic Hazard Characterization of the EUS

Dear Gil:

Enclosed please find the subject "Self Rating" questionnaire and answer sheet (three pages in all). It is important to the success of the project that you complete this questionnaire and return it to me as soon as possible. We will then incorporate your self-rating into our computational chain in strict confidence.

We are making steady and good progress in our project objectives. You will soon be informed about the extent of our progress and the time and place of our "Feedback Meeting" in October, 1983.

Thank you very much for your immediate attention, and have a good summer.

Sincerely yours,

Dae

Dae H. Chung
Principal Co-Investigator

DHC/sa

Enclosure

PS: If you have not yet submitted your bill, please send it to me indicating your consulting time. Danny

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bcc: D. L. Bernreuter
R. T. Langland
P. D. Smith

NRC

A. J. Murphy
L. Reiter/J. Kimball

Same letter sent to:

Dr. Alan L. Kafka
Weston Observatory

Mr. Richard Holt
Weston Geophysical Research, Inc.

Professor Arch Johnston
Tennessee Earthquake Information Center

Professor Tim Long
Georgia Institute of Technology

Professor James Lawson
Oklahoma Geophysical Observatory

Dr. Carl Stepp
EPRI

Professor Otto Nuttli
St. Louis University

Professor Ronald Street
University of Kentucky

Dr. Paul Pomeroy
Rondout Associates

Professor Nafi Toksoz
MIT

Dr. Carl Wentworth
USGS

Dr. Peter Basham
Dept. of Energy, Mines, and Resources
Ottawa Canada

Dr. Anne Stevens
Dept. of Energy, Mines, and Resources
Ottawa Canada

SELF RATING

1.0 Introduction

We have been receiving your responses from Questionnaire 2 and are in the final stages of developing the software to translate your opinions regarding the zonation and seismicity of the EUS into descriptions about the seismic hazard at selected sites. We want to again express our appreciation for your participation in this project.

As part of the elicitation process, we have asked you to give us your (a) best estimate of the seismic parameters (e.g., zonation, occurrence rate, upper magnitude cutoff, etc.) as well as (b) a range of values to which you associate a degree of confidence. In this context we consider confidence to reflect the degree to which you judge the historical data, your knowledge and experiences with the geologic and tectonic conditions in the EUS, and other relevant information to support a given response.

In the discussion (Section 1.3) in Questionnaire 1, we specifically pointed out that in questions involving a statement of confidence you should not be influenced by your level of expertise relative to the other members of the panel. Thus, we are able to develop a hazard curve with bounds for each individual which reflects the degree of confidence (or level of uncertainty) associated with the responses of that individual.

However, in addition to the hazard curve developed from the responses of each expert, it is important that we combine the hazard curves over all members of the panel to develop (a) a "best estimate" hazard curve which reflects the "best estimate" responses of the entire panel and (b) bounds for the hazard curve which reflect not only the uncertainties of the individual members but also the diversity of opinions between members of the panel. We propose to combine the best estimate hazard curves from each member and the uncertainty information by a weighted averaging procedure. To do this, of course, we need to determine an appropriate set of weights.

Although there are several weighting schemes (e.g., equal weights, LLNL derived weights), one set of weights, consistent with what was done on the previous (SEP) elicitation, is based on your appraisal of your expertise, i.e. self rating. We recognize some of the weaknesses and difficulties in eliciting and using self rating and we are investigating alternative weighting techniques. However, most weighting techniques are subjective and thus involve some of the same problems as self rating. Overall, we believe self rating to be a viable means of developing weights for combining the hazard curves for all members of the panel. Thus, we would ask you to self rate yourself with regard to your level of expertise about the geologic, tectonic and seismicity of the EUS.

In contrast to the previous elicitation when you were asked to self rate yourself with regard to (a) zone configuration, (b) maximum earthquake and (c) earthquake recurrence for each zone, our weighting method only allows for a single weight, i.e. a single weight which simultaneously reflects your

expertise with regard to zonation and seismicity. However, we do recognize that you may feel your level of expertise is not the same for the entire EUS. Thus, we have partitioned the EUS into four regions.

- o Northeast
- o Northcentral
- o Southeast
- o Southcentral

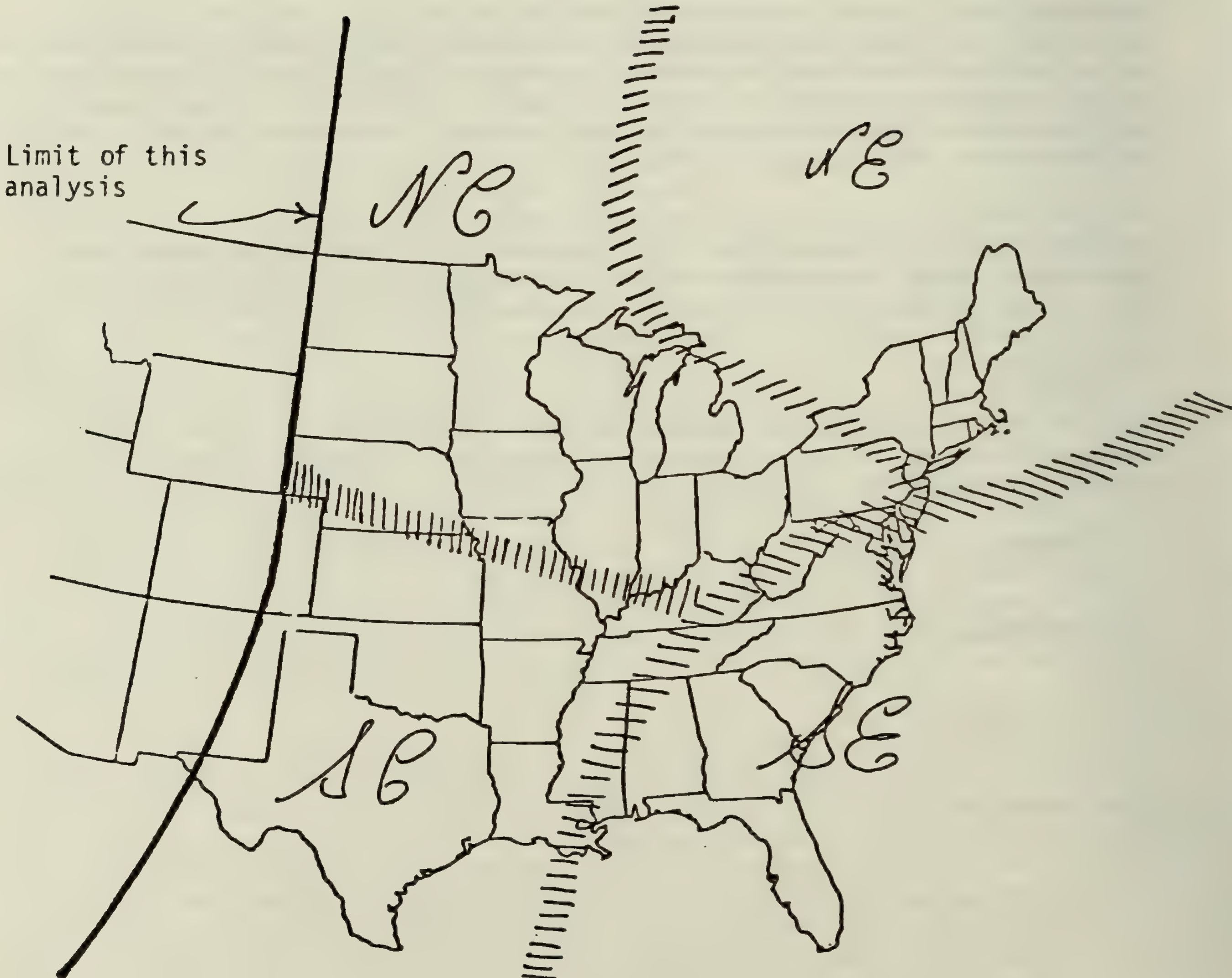
which have been labeled regions I-IV on the included map. The boundaries of the regions are also described in the following questionnaire. We would like you to self rate yourself for each of the four regions. We will combine your rating in the four regions to develop a single weight for the hazard based on your responses. The combination is based on the likelihood of the risk being initiated in a zone within each region.

In appraising your level of expertise in each of these regions, we ask that you use a 1-10 scale where low values indicate a low level of expertise and high values a high level of expertise. An integer value is not necessary, although not more than one decimal place (e.g. 7.3) is appropriate.

2.0 Question

For each of the four regions identified below, please indicate your level of expertise with regard to the geologic, tectonic and seismic characteristic within the region.

REGION		SELF RATING
I.	Northeast	________
II.	Northcentral	________
III.	Southeast	________
IV.	Southcentral	________



Identification of four regions of the Eastern U. S. based on a compilation of the seismic zonation expert maps developed in this study, combined with a map of Q_o-contours from Singh & Herrmann (1983).

FOURTH QUESTIONNAIRE - GROUND MOTION MODELS (Q4)

DEVELOPMENT OF EASTERN UNITED STATES GROUND MOTION MODELS
LAWRENCE LIVERMORE NATIONAL LABORATORY

1.0 BACKGROUND

We use the term Ground Motion Model to identify the equation used to estimate the ground motion at a particular site as a function of the "magnitude" of seismic energy released by an earthquake, the appropriate distance between the site and the source of energy released, and some factor to account for local site conditions. Typically, the ground motion model takes the functional form:

$$\ln(GMP) = C_1 + C_2 E + C_3 A(R) + C_4 S + (\text{Error term}) \quad (1\text{-}1)$$

where GMP = ground motion parameter of interest; e.g., PGA or PGV
C_i = constants
E = measure of seismic energy release - usually some magnitude measure or epicentral intensity.
R = appropriate distance measure
A(R) = attenuation term -- typically $A(R) = \ln R - C_5 R$
S = site factor term, e.g., S = 0 soil
= 1 rock

The error term accounts for the fact that the ground motion at a site due to a specific earthquake is a random variable, being affected by many more parameters than can be represented in a mathematical model such as Eq. (1-1). For example, the ground motion generating potential of an earthquake may be governed by dynamic stress drop and the area of release of energy in addition to the earthquake magnitude. Furthermore, ground motion is likely to be affected by the radiation pattern as well as "fine" details of the local site geologic column. Thus, the model in Eq. (1-1), less the error term, is intended to represent the "expected" or average ground motion at a site and the error term accounts for the random variation about that average value attributable to specific earthquakes.

In addition to the inherent random variation in ground motion about the average value, another source of uncertainty associated with ground motion models is attributable to the choice of parameters included in the model and the data base used to estimate the values of the coefficients $C_1,\ldots C_4$ in Eq. (1-1). These uncertainties, which we call modeling uncertainties, contribute to the uncertainty associated with the hazard analysis methodology. Modeling uncertainties are discussed in more detail in Section 2.4.

The ground motion model and the associated magnitude of the random variation have a direct effect on the hazard analysis. The estimates of the probability of exceedance are strongly correlated with the ground motion model. Changes in the model significantly affect the estimates of the hazard at a site. Thus, it is important that we select the most appropriate ground motion models for use in the hazard analysis.

The development of a ground motion model for the Eastern United States (EUS) is a difficult task for several reasons:

- There are few data on strong ground motion from EUS earthquakes.

- It is generally agreed that one cannot make direct use of a ground motion model developed from the Western United States (WUS), as data from a number of different sources indicate that the attenuation of seismic energy in the EUS is much different from that in the WUS.

- Recent work by Nuttli (1983b) suggests that the seismic source spectrum scales differently for EUS earthquakes than for WUS earthquakes.

In spite of these difficulties, given the paucity of strong ground motion data in the EUS, it is necessary to make use of WUS ground motion data and models and make corrections for the known differences between the WUS and EUS. The ground motion parameters (GMP) chosen for this analysis are the horizontal components of peak ground acceleration (PGA), peak ground velocity (PGV), and several spectral ordinates (SA) at frequencies ranging from 0.5 to 25 Hz.

In our earlier program for the Systematic Evaluation Program (SEP) we took what might be termed a "best estimate" approach; i.e., for a given site we developed a single best estimate hazard curve for each expert of the EUS Seismicity Panel. In keeping with this approach we only sought a best estimate model from our first EUS Ground Motion Panel. We did not achieve this objective and in the end we handled the ground motion model in an ad hoc fashion, primarily relying on sensitivity studies to demonstrate differences between models.

In our current effort, one of our objectives is to incorporate the improvements suggested by our reviewers into our overall approach. Two of the main areas for improvement are in the treatment of uncertainty and the manner in which the ground motion model is treated. This time we are concerned not only with a best estimate hazard curve but a detailed study of the uncertainty in the estimate of the hazard. We also want our results to be suitable for use in performing probabilistic risk assessments (PRA). Suitable input for a PRA requires a complete specification of the uncertainty in the hazard curve.

To achieve these objectives, it is necessary to put the current EUS Ground Motion Model Panel on the same footing as the EUS Seismicity Panel. This requires the identification and weighting of all ground motion models for the EUS which the Panel members deem sufficiently reliable to be included in the analysis.

Because it is possible to develop a large number of different models, we have attempted to provide in this report a framework for selecting from all possible models those which we feel are sufficiently reliable or credible to be used in the hazard analysis. To assist us in choosing the most appropriate models we ask the panel (see questionnaire, Section 7) to provide several pieces of information. For the short term, we ask you to select from seven

categories of already existing models the best model in each category and to provide your relative degree of belief in each. We also ask you to select from all the models the one which, in your opinion, provides the best overall estimates for the EUS. (Note: These models can change regionally.) For the long term, if in your opinion some new model could be developed or existing models improved by some additonal work, we ask you to provide a prescription of how to develop your "best estimate model" (or models if several are almost equally likely in your judgment). We may also have overlooked some models that you feel should be included. These should be added. In the feedback phase we will ask you to provide weights for all models. We will also address how best to deal with local site effects. Initially, we had planned to address this issue in this document, however, it would appear best to delay it until after the USGS workshop in July.

When making selections there are several considerations regarding how the models will be used that may affect choice and ranking of the various ground motion models. The first consideration is the choice of strong-motion components. Since our study is concerned with the horizontal components of ground motion, we have excluded any models based on the vertical component. In fact, there are very few such models available. Because there are two horizontal components, one must decide how they are to be used in the analysis. Models can be developed using the maximum or minimum component, the mean of the two components, the vector combination of components, or both components. In our analyses we will be using the mean of the parameters established from the two horizontal components . Since it is relatively simple to relate predictions based on other definitions to estimates of the mean, the particular definition used should not affect your choice or ranking of models. However, your choice of the value of uncertainty to be associated with these predictions should take this into consideration. The use of the mean of the two horizontal components has been found to result in a smaller standard error than the use of either the maximum component or both components.

The second consideration is the definition of the source-to-site distance. The way the hazard analysis is performed, earthquakes are essentially modeled as point sources at the surface of the earth. This is consistent with the definition of epicentral distance. Therefore, ground motion models utilizing epicentral distance as the measure of source-to-site distance are the most appropriate models to be used with the hazard code. A problem arises when a ground motion model uses a distance measure other than epicentral distance. Three such models, two by Campbell (1981b, 1982) and one modified from Joyner and Boore (1981), referred to as the SSMRP model, are offered for your consideration. Their use of closest distance to the fault rather than epicentral distance has substantially reduced the standard errors associated with these models. While this suggests that models based on fault distance are better predictors of strong ground motion than epicentral models, one must consider their use before making such a decision. For example, such models, when used with a hazard analysis based on epicentral distance, will tend to underestimate the ground motion expected at the site for distances close to the source (see Appendices C-B and C-C for a more complete discussion). This should be kept in mind when selecting and ranking the various ground motion models and when specifying an appropriate value for the uncertainty to use in

the analyses. If the panel members feel the use of epicentral sources in the hazard code is a severe limitation to their selection of the best models, they are asked to indicate this in the questionnaire.

The last consideration is in regards to the strong-motion parameter to be used. The parameter of interest for our study is pseudo-relative velocity representing frequencies of 0.5 to 25 Hz (periods of 0.04 to 2 sec.). However, there are very few EUS ground motion models available that predict this parameter directly. The current state-of-practice is to develop response spectra from peak acceleration and/or peak velocity and standard spectral shapes. For this reason, we require ground motion models based on peak acceleration and peak velocity. Because there are fewer velocity models than acceleration models, the unavailability of certain models may also affect your choice of the "best model" in a particular category. Each of these parameters will be ranked separately. Several factors will have to be considered when selecting and ranking spectral models. One factor is whether the model is based on a regression of individual ordinates or based on a spectral shape. A second factor is the relative appropriateness of the various spectral shape models. Another factor is whether the spectral shape model requires estimates of both peak acceleration and peak velocity and whether both are available.

In Section 2 we describe the framework we have selected to categorize the different ground motion models. In Section 3 we provide a generic evaluation of the different categories defined in Section 2. In Section 4 we provide specific examples and comparisons between the acceleration models. In Section 5 we discuss velocity and spectral models. In Section 6 we discuss the available EUS strong-motion data. Section 7 contains the questionnaire.

2.0 INFERRING EASTERN U.S. GROUND MOTION

There are at least three general approaches that could be used to develop EUS ground motion models:

1. Those that use site intensity as an intermediate variable (I),
2. Those that use ground motion measurements directly (D), and
3. Theoretical modeling (T).

2.1 Intensity Based Models

This category includes all models developed in a formal manner by combining a MM intensity-attenuation relation, such as

$$I_s = C_1 + C_2 I_o + C_3 \ln R + C_4 R \tag{2-1}$$

with a relation between site intensity (I_s) and various ground motion parameters (e.g., PGA), to get a relation between GMP, source size and distance.

For each intensity-attenuation relation there are a number of different ways that the relation between site intensity and ground motion parameters can be developed and combined with the intensity-attenuation relation. To organize our discussion we will sort all such approaches into one of five basic methods:

(I-1) No weighting
(I-2) Distance weighting
(I-3) Magnitude weighting
(I-4) Magnitude and distance weighting
(I-5) Semi-empirical

The following discussion will briefly describe each of these approaches and the basic assumptions required for each. We will also attempt to describe the inferences involved in these assumptions regarding the prediction of ground motion in the EUS. The reader may then compare these inferences regarding EUS ground motion with what he believes to be the true conditions prevailing in the EUS to help him decide which models are more appropriate.

Method I-1 (No Weighting). This method simply relates site intensity to ground acceleration, ground velocity, and/or the response spectrum, as obtained from existing strong ground motion records. Thus,

$$\begin{aligned} I_s &= F(I_o,R) && \text{based on EUS data} \\ GMP &= G(I_s) && \text{based on WUS data} \end{aligned} \tag{2-2}$$

This method assumes that ground motions are the same for the same site intensity in both regions, regardless of the size or distance associated with this intensity. Thus, differences in the attenuation of I_s between the two

regions (i.e., differences in the relation $I_s = F(I_o,R)$) require that predictions of GMP in the EUS for fixed I_s be associated with predictions in the WUS based on data obtained at shorter distances or from larger magnitudes. This will result in ground motion models for the EUS that predict higher amplitudes than similar models in the WUS for similar magnitudes and distances. Because this approach results in predictions in the EUS that represent WUS data of higher magnitudes or shorter distances, inferences regarding the effect of this approach on spectral shape and duration of strong ground motion in the EUS are not clear. While higher magnitude data will be associated with longer durations and relatively higher low frequency content, data obtained at shorter distances will be associated with shorter durations and relatively greater high frequency content. This would imply that on the average predictions of GMP in the EUS will probably be associated with ground motions of about the same duration and spectral content as those in the WUS.

Method I-2 (Distance Weighting). This method relates the ground motion parameter to site intensity and distance, assuming that the ground motions are the same for a similar site intensity and distance in the two regions. Thus,

$$I_s = F(I_o,R) \qquad \text{based on EUS data} \qquad (2\text{-}3)$$
$$GMP = G(I_s, R) \qquad \text{based on WUS data}$$

This method, which can be called "distance weighting," requires that predictions of GMP in the EUS for fixed I_s and R be associated with predictions in the WUS based on data obtained from larger magnitude earthquakes in order to accommodate differences in the attenuation of I_s between the two regions. This will result in ground motion models for the EUS that predict higher amplitudes than similar models in the WUS for similar magnitudes and distances. Because this approach results in predictions in the EUS that represent WUS data of similar distances but higher magnitudes, we may infer that EUS predictions will be associated with ground motions having longer durations, greater low frequency content, and about the same amount of dispersion as WUS predictions at the same magnitude and distance. The enhanced low frequency content will result in a "broader" predicted response spectrum in the EUS.

Method I-3 (Magnitude Weighting). This method relates the ground motion parameter to site intensity and magnitude, assuming that the ground motions are the same for a similar site intensity and magnitude in the two regions. Thus,

$$I_s = F(I_o,R) \qquad \text{based on EUS data} \qquad (2\text{-}4)$$
$$GMP = G(I_s, M) \qquad \text{based on WUS data}$$

This method, which we refer to as "magnitude weighting," requires that predictions of GMP in the EUS for fixed I_s and M be associated with predictions in the WUS based on data obtained at shorter distances in order to accommodate differences in the attenuation of I_s between the two regions. This will result in ground motion models for the EUS that predict higher amplitudes than similar models in the WUS for similar magnitudes and distances. Because this approach results in predictions in the EUS that

represent WUS data of similar magnitudes but shorter distances, we may infer that EUS predictions will be associated with ground motions having shorter durations, greater high frequency content, and less dispersion than WUS predictions at the same magnitude and distance. The enhanced high frequency content will result in a "narrower" predicted response spectrum in the EUS.

Method I-4 (Magnitude and Distance Weighting). This method relates the ground motion parameter to site intensity, magnitude and distance. Thus,

$$I_s = F(I_o,R) \qquad \text{based on EUS data} \qquad (2\text{-}5)$$
$$GMP = G(I_s, M, R) \qquad \text{based on WUS data}$$

This method requires the assumption that the ground motions are identical for the same I_s, M, and R in the WUS and EUS. Thus, in order to accommodate differences in intensity attenuation between the two regions, predictions of GMP in the EUS will be associated with WUS data exhibiting higher than average site intensities for a given magnitude and distance. These data will tend to be associated with relatively rare properties of the source, path or site that result in higher than normal amounts of damage. This will result in ground motion models for the EUS that predict higher amplitudes than similar models in the WUS for similar magnitudes and distances. This method infers that EUS predictions will be associated with ground motions of either higher amplitudes, longer durations, enhanced frequency content, or some combination of these as compared to WUS predictions. Because this approach results in predictions in the EUS that represent WUS data at similar distances, they will represent ground motions having similar dispersion characteristics.

Method I-5 (Semi-Empirical). All of the above methods are based on a formal substitution of the results of a regression analysis between the GMP and site intensity (using WUS data) into a relation between site intensity, epicentral intensity and distance (EUS data) to get a relation between GMP, epicentral intensity and distance for the EUS. There are alternative approaches; e.g., Nuttli and Herrmann (1978) used Method I-4 but included a free parameter which they evaluted using judgment and some EUS ground motion data. Battis (1981) assumed that the ground motion in the epicentral region would be similar in all regions for earthquakes of the same epicentral intensity, and that PGA at the limit of the felt area is equal to 6 cm/sec^2.

2.2 Direct Models

Under this category we include all the approaches that derive ground motion models directly from the data without the use of site intensity as an intermediate variable. For the WUS, typical models of this class are those developed by Joyner and Boore (1981) and Campbell (1981a). Unfortunately, for the EUS there isn't sufficient data to perform such regression analyses. Thus, for the time being, one must resort to a semi-empirical approach to arrive at a model for the EUS.

There are many possible ways of developing semi-empirical models. For ease of discussion we separate them up into two major subcategories, D-1 and D-2. Category D-1 includes all those models where it is assumed that the ground motion "near" the source of energy release is the same in the EUS and WUS, and that at larger distances the differences in the ground motion between the two regions is due solely to differences in anelastic attenuation. Nuttli (1979) and Campbell (1981b) have developed models based on this assumption.

Category D-2 includes those semi-empirical models for which it is assumed that, in addition to differences in anelastic attenuation between the EUS and WUS, the ground motion scales differently in the EUS than in the WUS with source size (i.e., the basic source parameters of the earthquake are on the average different between the two regions). Nuttli's most recent models (Appendix A) fall into this category.

2.3 Theoretical Models

This category includes the approaches that rely on numerical modeling techniques, making use of some simple or complex theoretical model to compute the ground motion at a site. Examples of models in this category are: Herrmann and Goertz (1981), Savy (1979, 1981), and Apsel et al. (1982). This is a very large category which undoubtedly would have a number of subcategories. However, at this time it does not appear to us that any of the methods or results are sufficiently advanced to use in the type of hazard analysis required for this project. Although such methods show promise, they are not yet advanced to a state that one can use them without excessive computation costs. In addition, in view of the lack of correlation between earthquakes and known tectonic structures in the EUS, it is not possible to develop with any degree of accuracy the necessary source parameters for such models. Thus, in what follows, very little will be said about theoretical models and such models will not be included unless specifically proposed by one of the Panel members.

2.4 Modeling Uncertainties

Given an earthquake of magnitude M and distance R from a site, the ground motion model represents a statistical description of the ground motion at a site. In the case of an earthquake, the actual motion of the site is not likely to be exactly as predicted by the model. Although there are several reasons for this, they can be summarized as follows:

- The model is only a mathematical representation of the physical world which cannot capture all of the details of reality. It is unlikely that all relevant parameters have been included in the model. Furthermore, the values of the coefficients in the model are based on a limited sample of earthquakes. Thus, for a specific earthquake, the model cannot be expected to predict the exact ground motion value. Since for the EUS the coefficients are determined by use of data from other regions and/or theoretical or semi-empirical considerations, there is an added degree of uncertainty in modeling EUS ground motions.

- Even if the mathematical model was an exact representation of ground motion characteristics, it only represents an average or expected motion at a site for a specified magnitude and distance. Due to random variations in source, path, and site characteristics, it cannot predict the actual ground motion for a specific earthquake.

  Both types of variation contribute to the uncertainty in predicting the ground motion for a specific earthquake. We believe it is important to distinguish between these uncertainties which we label modeling and random. The latter variation is, of course, the inherent random variation that occurs in the physical world. In the hazard analysis this type of variation is recognized by assuming that the ground motion has a distribution about the predicted value. We describe this distribution, in our hazard analysis, by a lognormal distribution, the median of which is estimated by the ground motion model. A complete specification of the distribution requires some measure of the variation in the ground motion parameter about its median value. A convenient way of expressing this variation is in terms of the standard deviation of the natural logarithm of the GMP. However, data necessary to assess this variation (i.e., ground motion data at the same location from several earthquakes of similar magnitude and distance from the site) are not available for the EUS. Thus, it is necessary to elicit expert opinion about this variation. The former variation is what we call modeling uncertainty. It arises because we have very limited data sets and an imperfect understanding of the functional form and parameterization of the ground motion model. This uncertainty will be included by the use of several ground motion models together with subjective weights assigned by panel members.

3.0 EVALUATION OF APPROACHES

3.1 General Discussion

Of the many possible models that can be developed, which one is "best"? The absence of actual data makes it impossible to give an unqualified answer. Thus, we must rely on expert judgment to help us select the best models.

At least three major factors must be considered when developing an EUS ground motion model. These three factors represent differences between the EUS and WUS relative to:

1. Regional attenuation of strong ground motion,
2. Scaling of ground motion with earthquake magnitude, and
3. The variability in ground motion between earthquakes of the same magnitude introduced by source, path and site effects.

The selection and ranking of ground motion models from those available should be based in part on an assessment as to how well they account for the above items. For example, all of the general approaches outlined above include differences in regional attenuation but in different ways. The approaches which use intensity data make the assumption that strong ground motion in the EUS attenuates at a rate proportional to that of intensity, this proportion being the same as that in the WUS. The semi-empirical approaches generally introduce a correction based on regional measurements of the attenuation of low energy seismic waves.

Evaluation of the general approaches outlined above is difficult because it is possible to develop many specific models for each class. However, there are some general comments that can be made which may be of use in comparing one model to another.

3.2 Intensity Based Models

We noted that there were at least five possible methods which use intensity to make estimates of the ground motion. However, in general, there seems to be no method free of theoretical deficiencies for using intensity data from the WUS to estimate ground motion in the EUS. One problem is that, in estimating one random variable (z) from another (x), introduction of a third random variable (y), used as an intermediary, results in both a bias in the mean estimate of z and a larger modeling uncertainty in estimating z than would be the case if z were to be estimated directly from x. In the case of estimating ground motion, the procedure of estimating site intensity from epicentral intensity, then estimating ground motion amplitudes from site intensity, results in amplitudes that are less dependent on earthquake size and distance than would be the case if ground motion were to be estimated directly. Such procedures can work well if there is a strong correlation between the variables. Such does not appear to be the case. This is not surprising as the intensity scale was not developed with such correlations in mind.

inclusion of a distance or magnitude term in the correlations of GMP to site intensity (I_s),

$$GMP = G(I_s, R) \tag{3-1}$$

or

$$GMP = G(I_s, M) , \tag{3-2}$$

tends to increase the dependence of GMP on M and R (i.e. it affects the relationships in the correct manner), making such correlations appear to be better than relationships of the type GMP = G(I_s). However, inclusion of M or R does not ensure that unbiased estimates will be made. In fact no intermediary parameter can do that, unless it is perfectly correlated with the first parameter (in this case I_s) or with the last (GMP).

For the intensity based approaches, regional scaling of ground motion with earthquake magnitude is primarily accounted for by the way site intensity at some distance R scales with epicentral intensity, the regional relation between epicentral intensity and magnitude, and, as discussed in Section 4 (see Eq 4-19), how the various GMPs are related to site intensity. This last factor (I_s GMP relation) is of concern because it is obtained from data in the WUS. The magnitude weighting approach introduces a secondary correction for magnitude scaling; however as discussed in Bernreuter (1981), this additional weighting is not introduced to account for regional differences in scaling of ground motion with magnitude, but rather help account for regional differences in attenuation and the fact that the same intensity occurs at much greater distances for large earthquakes as compared to smaller earthquakes. Battis (1981) argued that making the assumption that ground motion was the same in different regions at the same epicentral intensity allows for a regional correction for scaling with magnitude to be introduced through the relation between magnitude and epicentral intensity.

3.3 Direct Models

The most reliable ground motion model to use in a seismic hazard analysis, at least at this time, would be one obtained by direct regression on the data. For such results to be valid, one needs sufficient data from a number of earthquakes to be able to obtain reliable estimates for the coefficients of the model. Such data are not currently available in the EUS, requiring a semi-empirical approach to develop such models.

Semi-empirical models D-1 and D-2 are difficult to assess as a group because many diverse assumptions can be made. Many of the semi-empirical models introduce a correction for regional attenuation based on regional measurements of the attenuation of low energy seismic waves. In general, such models have a higher rate of attenuation at larger distances than the intensity based models. Most such models rely heavily on strong motion data from WUS earthquakes.

One key element in our classification is the question of the differences in average source parameters between EUS and WUS earthquakes and the implication this has on ground motion. The basis for such differences is discussed by Nuttli (1983a b). The impact of these hypothesized differences lies in the way GMP scales with magnitude. Semi empirical approaches in category D 2 introduce a regional correction for scaling of ground motion with magnitude. These corrections are generally based on theoretical considerations.

3.4 Other Factors

For several of the proposed categories we need to know the magnitudes of the earthquakes in the EUS and WUS on a scale which allows them to be directly compared at frequencies of 1 Hz and greater. The m_b scale appears to be well suited for this, but there are problems. First, the M_L scale rather than the m_b scale is commonly used for WUS earthquakes. Furthermore, m_b values for WUS earthquakes, as determined by the USGS, are often unreliable because they are usually based on P-wave amplitudes at distances of less than 2500 km. At these short distances two problems must be faced: the large variation of P-wave amplitude due to variations in upper-mantle structure and the known difficulties with the Gutenberg-Richter calibration function. (The latter problem can be reduced by using the Veith-Clawson calibration function used by DARPA.) For the larger WUS earthquakes (m_b > 5.5), there are sufficient P-wave observations at distances greater than 2500 km to overcome these problems. But some seismologists who have studied the amplitudes of P waves from underground nuclear explosions at the Nevada Test Site conclude that anomalous upper-mantle structure causes m_b values for WUS events to be underestimated by about 0.3 m_b units. Using such data, Chung and Bernreuter (1981) and Herrmann and Nuttli (1982) conclude that the two scales (m_b in the EUS and M_L in the WUS) are approximately equivalent in the M_L=5 range. Using standard measurements, an M_L of about 5.0 for a WUS earthquake would be comparable to an m_b of about 4.6 for an EUS earthquake.

In addition to the corrections for differences in regional attenuation and magnitude scaling, there may be a need to correct for possible regional differences in the variability in ground motion between earthquakes of the same magnitude. This random variability arises due to differences in the rupture process, complexity of the travel path, and local site geology. For example, there is some evidence that earthquakes of the same magnitude are more similar in mid-plate areas, such as the EUS, than along plate margins. If this is true, we would expect to see less source induced random variability in the ground motion in the EUS than in the WUS. In addition, the travel path is certainly less complex in the EUS than along plate margins which would also lead to less variability. For this study the variability in the estimate of the ground motion for a given magnitude and distance is generally measured by the standard deviation of the natural logarithm of the parameter, σ_{lnGMP}. Thus, for the EUS ground motion model we might expect contributions of source and propagation path variability on σ_{lnGMP} to be smaller than for the WUS. However, there are not sufficient data in the EUS to evaluate such an hypothesis.

The value of σ_{lnGMP} is a measure of the total uncertainty including the fact that the data used to develop the ground motion model was obtained from a number of different sites with very different site geology. There have been only a few studies which have attempted to sort out the relative contribution to the variability in the ground motion from these factors (Bernreuter, 1979, McCann and Boore, 1982). At this stage we are only addressing standard "rock" and "soil" sites. Nevertheless, it should be kept in mind that, in general, near-surface rock is more competent (e.g., higher V_s, V_p, ρ) in the EUS than in the WUS. Also the soils in many areas of the EUS are significantly different (e.g., Glacial Deposits) than those at sites that make up the existing strong motion data base. These factors need to be kept in mind when providing estimates for σ_{lnGMP} in the question- naire. As noted in the introduction, we will address shallow soil sites and other anomalous site conditions as special cases.

4.0 REVIEW OF ACCELERATION MODELS

4.1 Intensity Based Models

Intensity Attenuation Relations

Development of an intensity attenuation model requires a relation of the form,

$$I_s = F(I_0 \text{ or } M,\ R) \qquad (4\text{-}1)$$

The first consideration in the development of such a relation is whether $F(I_0,R)$ is to be derived from intensity data of a single well recorded earthquake, assuming all earthquakes of intensity I_0 are the same, or from more limited data of several earthquakes. If one uses a single well recorded event, questions arise as to the appropriateness of the data in representing the attenuation characteristics of other earthquakes and how to scale the ground motion between earthquakes. If data from a number of earthquakes with sufficient variation in epicentral intensity is used, then these problems are taken care of. Unfortunately, this latter alternative is not viable at present, because even though considerable intensity data exists, very little of it is in a form that can be used to develop the required relations. Only a few studies have been made of individual earthquakes to develop the required equations, and no study that we are aware of has used individual intensity reports from a number of earthquakes to correctly estimate the coefficients of Eq. (4-1). Because of the large variation in intensities, considerable data are required--particularly at the lower intensity levels. Typically, such data are not available.

Because individual intensity data are seldom available, the coefficients of Eq. (4-1) are more commonly computed using an equivalent or average distance for each intensity. This "Equivalent-R" approach is convenient if, in place of intensity reports, one works with isoseismals. Isoseismals are useful because they have been developed for a number of earthquakes, including most of the significant historic earthquakes. Results based on the two approaches can be considerably different as illustrated by Fig. 4-1 taken from a study by Weston Geophysical Corp. as documented in Bernreuter (1981b). The curve labeled 1 was obtained by direct regression on the data for the Ossippee earthquake and the curve labeled 3 was obtained using distances to isoseismals. The triangles represent the individual intensity reports. As can be seen from Fig. 4-1, Eq. (4-1) is poorly constrained by the data.

Figure 4-2 shows the fit of the equation

$$I_s - I_0 = C_1 + C_2 \ln R + C_3 R \qquad (4\text{-}2)$$

to the individual intensity data from each earthquake listed in Table 4-1. While no one has combined such data from a wide range of earthquakes to develop the required coefficients of Eq. (4-2), several investigators have used isoseismals to develop generic relations. Included in Fig. 4-2 is such a relation developed by Gupta and Nuttli (1976). Since the Gupta-Nuttli relation was based on isoseismal data rather than individual intensity

reports, we have reduced the C_1 coefficient by 0.5 intensity units to make it compatible with the other expressions in Fig. 4.2. We will refer to this relation later as the modified Gupta-Nuttli relation.

GMP - Site Intensity Relations

To complete the intensity based ground motion models, one also needs a relation between site intensity and ground motion. As discussed in Section 2, there are several functional forms this relation can take. Also, there are several data sets that can be used. For example, Fig. 4-3 shows the data base developed by Cal Tech and Fig. 4-4 shows the data base developed by Murphy and O'Brien (1977) for NRC. (Note: only the U.S. data are shown in Fig. 4-4.) Each investigator has "customized" his data set. Nevertheless, Figs. 4-3 and 4-4 give an indication of how much data exists and how little data there are to define the relation between the GMP and site intensity at the more important higher intensity levels.

TABLE 4-1
Summary of Earthquakes Used in the Intensity Data Base

Name	Date	Maximum Intensity	Analysis Source
Southern Illinois	11/9/1968	VII	G. A. Bollinger
Ossippee	11/20/1940	VII	R. J. Holt
Giles County	5/31/1897	VII-VIII	G. A. Bollinger
Charleston	8/31/1886	X	B. A. Bollinger

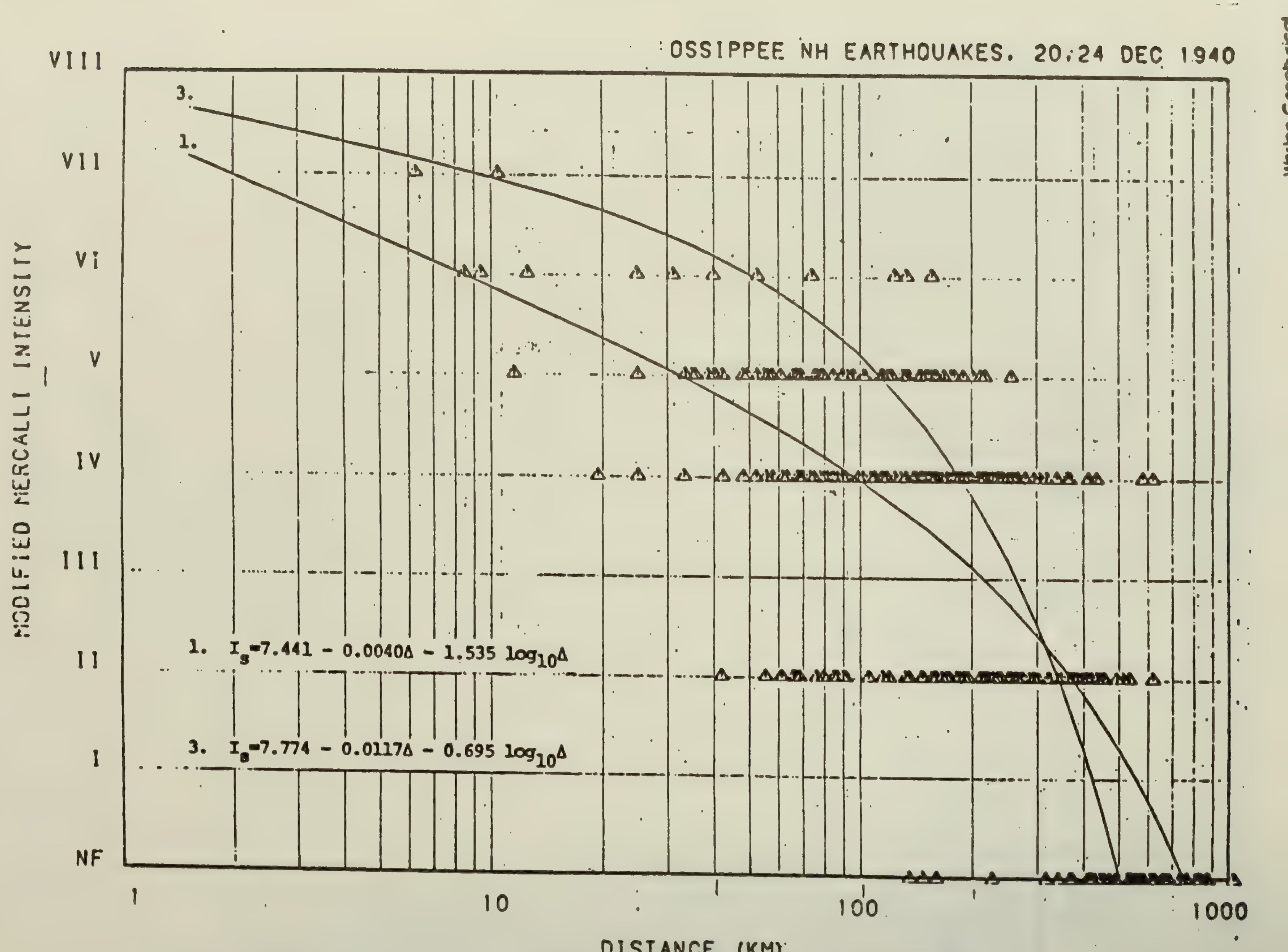


Fig. 4.1 Site intensity versus distance for the Ossippee N.H., earthquake of December 1940. Taken from Weston Geophysical Company

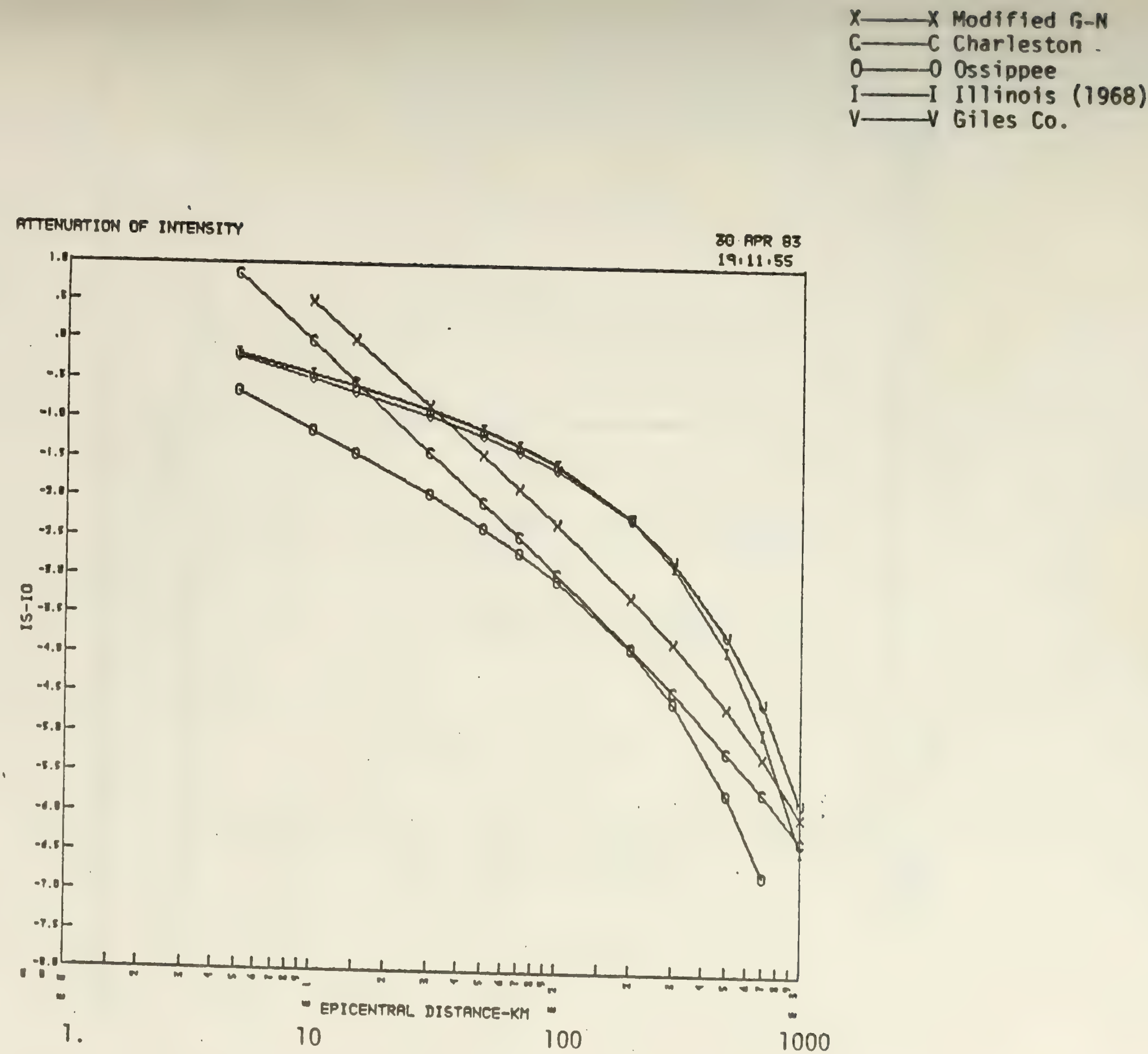


Fig. 4.2 Comparison of the "modified" Gupta-Nuttli relations with available data.

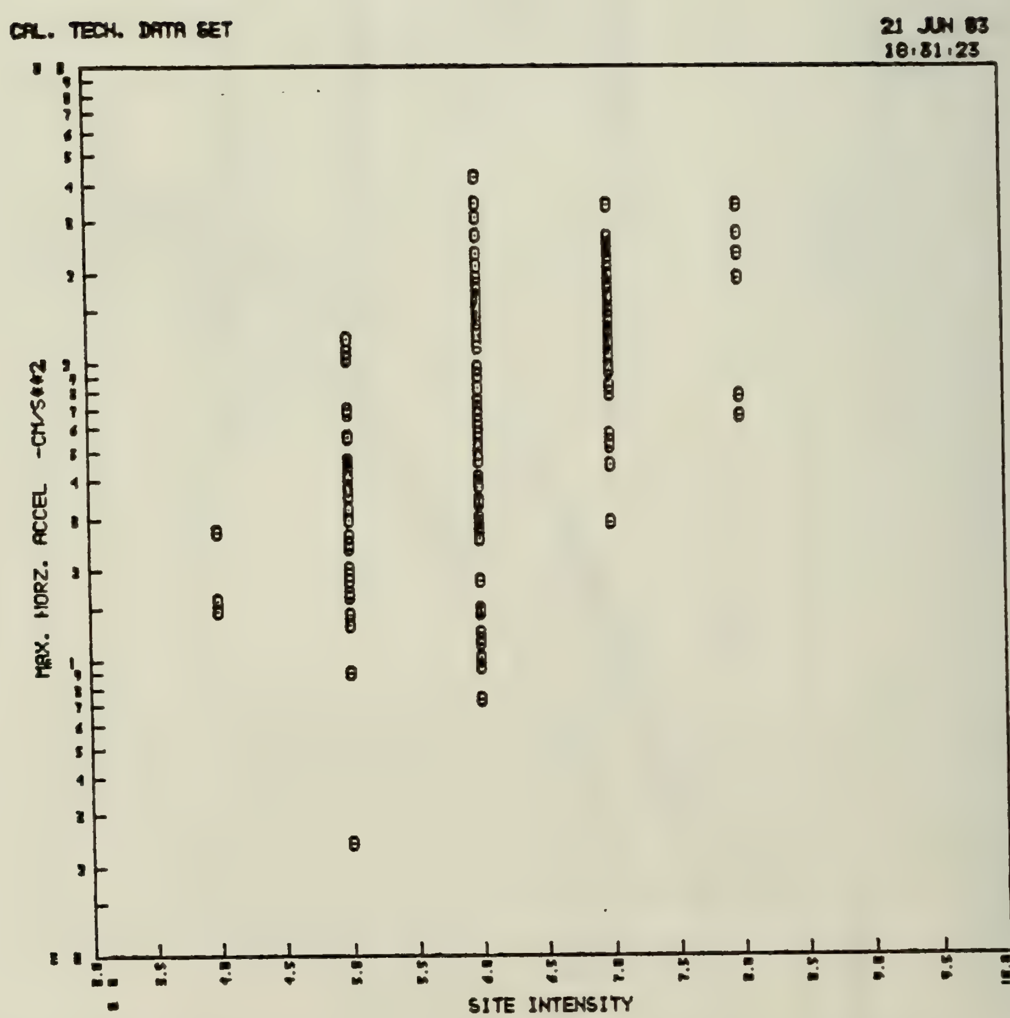


Fig. 4.3 Cal tech data base of acceleration versus site intensity.

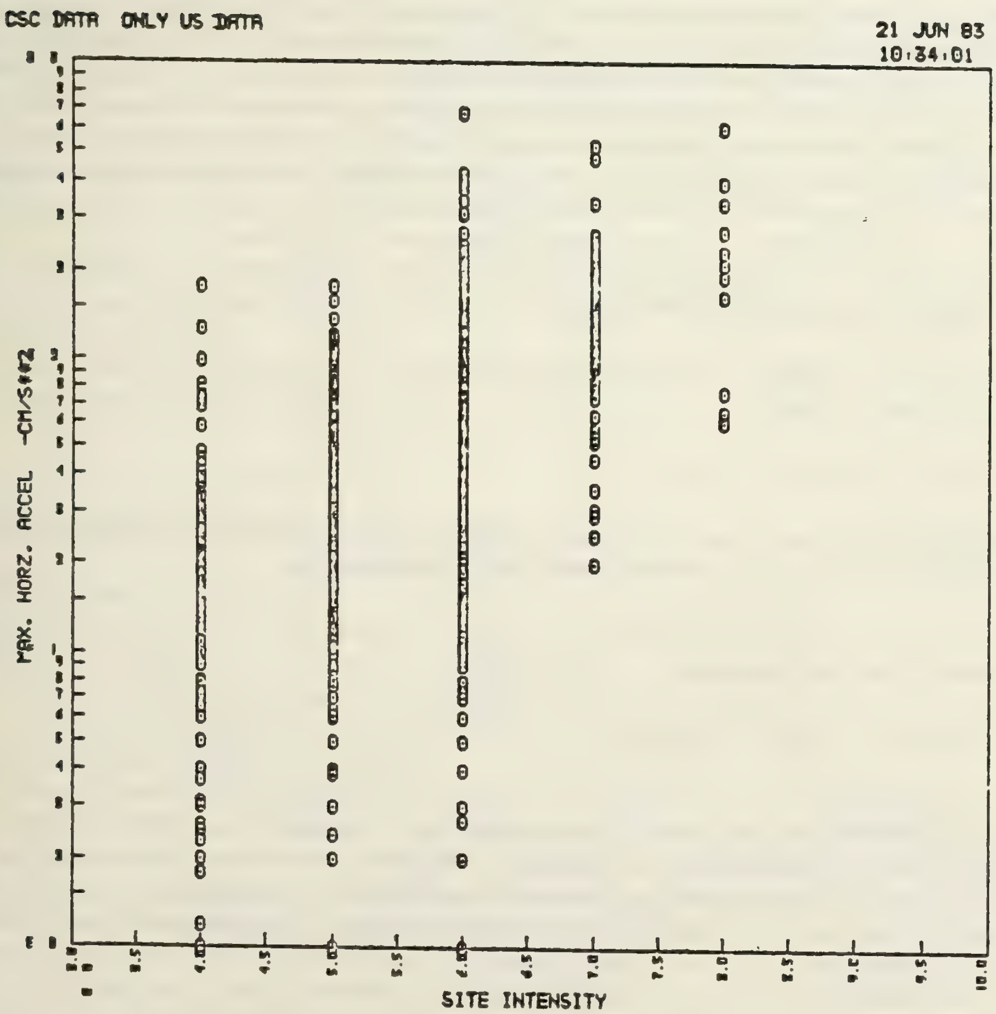


Fig. 4.4 Murphy and O'Brien data base of acceleration versus site intensity.

In addition to different data sets, there are a number of different ways the regression analysis can be performed to obtain estimates of the coefficients of the model. For example, McGuire (1977) found for medium sites

$$\ln(a) = -0.83 + 0.85\ I_s \tag{4-3}$$

and Trifunac (1976) found

$$\ln(a) = -0.19 + 0.67\ I_s + 0.33S \tag{4-4}$$

McGuire and Trifunac used approximately the same data set, however, the forms of the regression were different. McGuire separated his data into two sets (soft and medium sites) and performed separate regression analyses on each data set. Trifunac introduced a site variable S which has a value of 0, 1, or 2 depending upon the site type (see Sec. 7 for a definition of s). Trifunac and Brady (1975) used the same data set as Trifunac, but performed regression analyses on the logarithm of the mean acceleration for each intensity level, independent of site type. Their resulting expression was

$$\ln(a) = 0.032 + 0.69\ I_s \tag{4-5}$$

Murphy and O'Brien (1977) found by using a more extensive data set not segregated by site type

$$\ln(a) = 0.58 + 0.58\ I_s \tag{4-6}$$

Murphy and O'Brien used just the peak horizontal component, whereas McGuire, Trifunac, and Trifunac and Brady used both components.

Site type can have a significant effect on the derived relation. For example, McGuire found for soft sites

$$\ln(a) = 0.27 + 0.6\ I_s \tag{4-7}$$

which is significantly different than his expression for medium sites (Eq. 4-3). This dependence on site type may be an important consideration in the selection of the "best" relation between the GMPs and site intensity as these expressions should be derived in a manner consistent with Eq. (4-1). All of the available intensity attenuation relations were derived without regard to site type, because site data is not generally available for the intensity reports. In addition, it is doubtful in our opinion that the value of intensity assigned to each PGA value (a in the above expressions) in the various data bases can be said to be truly representative of the intensity at the recording site. For these reasons, one might prefer GMP-I_s relations that are developed without regard to site type.

An even more significant problem involves the use of low intensity data in the regression analysis. For example, the Cal Tech Data set used by Trifunac, McGuire, and Trifunac and Brady includes MM IV and V data. However, the ground motion data for these intensities may not be representative because the data set was developed using only digitized accelerograms. The criteria for

selecting accelerograms to be digitized required that the level of ground shaking be "significant" or that the records be associated with an earthquake with "significant" damage. In our view, such a selection process would tend to bias the data towards high PGA records, particularly at the lower intensity levels. In the least squares fitting process this would tend to reduce the coefficient of the I_s term, thereby reducing the estimate of PGA at high intensity levels.

The data set developed by Murphy and O'Brien also has some bias. Although the set of MM IV and V data is more complete than the Cal Tech set, in order to be included, the accelerograph had to trigger, the records read, and the values reported. Such values are often only reported if the level of acceleration is at least 0.05g (this is standard practice for the USGS). Thus, The MM IV and V set of Murphy and O'Brien is probably also biased towards higher values of PGA. Eq. (4-6) suffers from a further bias because in performing their regression analysis Murphy and O'Brien only included PGA levels greater than 10 cm/sec^2.

To assess the impact of incompleteness at the lower intensity levels, we have recomputed the coefficients of Eq. (4-6) using U.S. data without the 10 cm/sec^2 cutoff. We found

$$\ln(a) = -1.69 + 0.86\, I_s \tag{4-8}$$

if MM IV-X data are included and

$$\ln(a) = -2.32 + 0.96\, I_s \tag{4-9}$$

if only MM V-X data are used.

Equations (4-3), (4-4), (4-6), (4-7) and (4-9) are compared in Fig. 4-5. Also shown on Fig. 4-5 are the mean log acceleration levels for MM V-VIII level based on the Murphy and O'Brien data for the U.S. shown on Fig. 4-4. A value of 1000 cm/sec^2 was chosen for MM X.

As seen by the scatter of data at each intensity level, the correlation between PGA and site intensity is poor. Different methods have been proposed to improve this correlation. For example, studies show that the residuals of GMP-I_s relations are strongly correlated with distance. This leads naturally to regressions of the form

$$\ln(a) = C_1 + C_2 \ln R + C_3\, I_s \tag{4-10}$$

which we have denoted as "distance weighted" models. For medium sites, McGuire (1977) found

$$\ln(a) = 1.45 - 0.359 \ln R + 0.68\, I_s \tag{4-11}$$

X E(Log A) for each
intensity level
(CSC data ~ only l

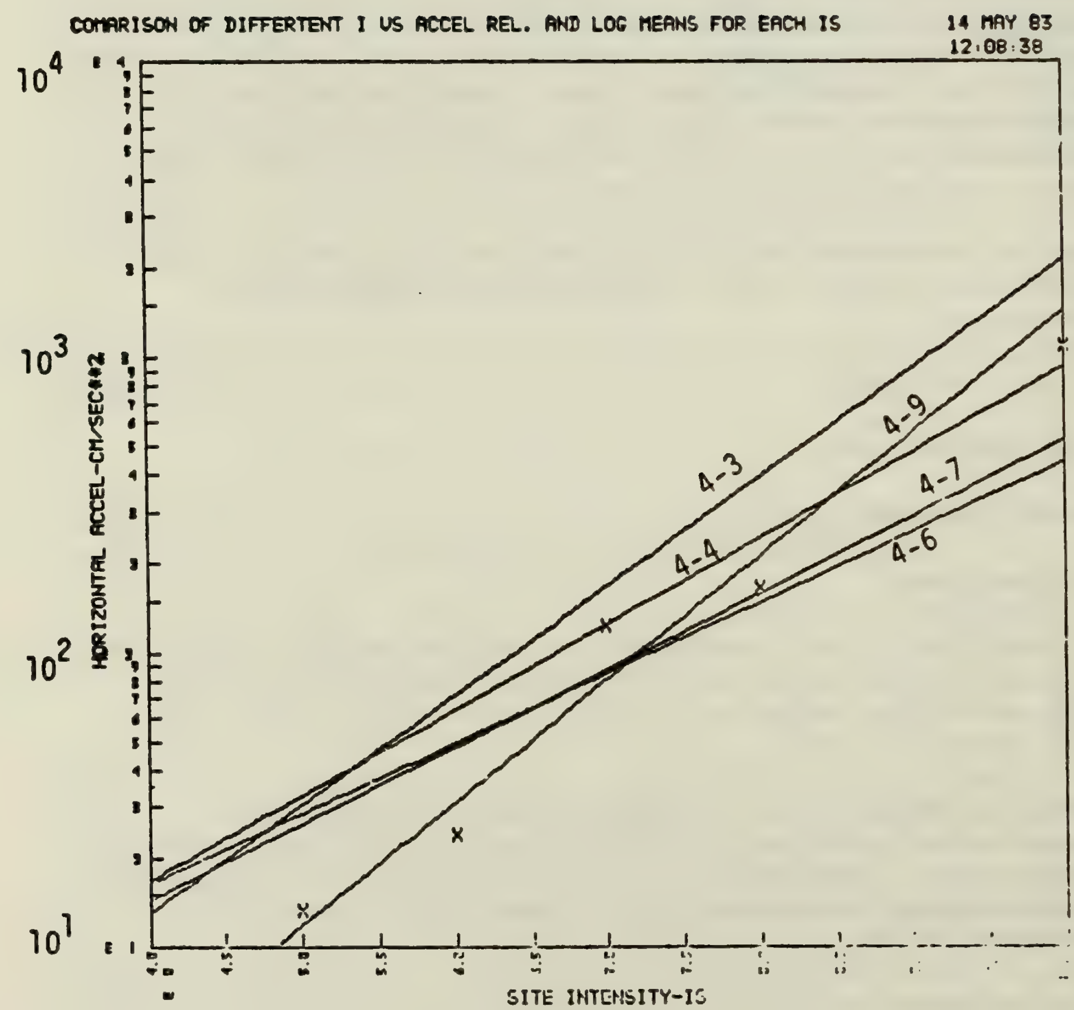


Fig. 4.5 Comparison of several accelerations versus site intensity equations.

and for soft sites

$$\ln(a) = 2.01 - 0.313 \ln R + 0.51 I_s \qquad (4\text{-}12)$$

In our earlier study (Bernreuter 1981a) we found

$$\ln(a) = 1.79 - 0.323 \ln R + 0.57 I_s \qquad (4\text{-}13)$$

Eq. (4-13) was obtained using the Cal Tech data set without regard to site type. It is in general agreement with McGuire's results, falling somewhere between his predictions for soft and medium sites. Neither Murphy and O'Brien, Trifunac, nor Trifunac and Brady considered a regression of the form of Eq. (4-10).

Our earlier study (Bernreuter 1981a) appears to be the only case which has considered a "magnitude-weighted" model of the form

$$\ln(a) = C_1 + C_2 M + C_3 I_s \qquad (4\text{-}14)$$

We evaluated the coefficients of Eq. (4-14) using a modification of the Cal Tech data set and a weighted regression analysis to obtain

$$\ln(a) = 0.96 - 0.13M_L + 0.63 I_s \qquad (4\text{-}15)$$

In addition to Eq. 4-6, Murphy and O'Brien also developed a relation of the form

$$\ln(a) = C_1 + C_2 M + C_3 \ln R + C_4 I_s$$

They found for U.S. accelerations greater than 10 cm/sec^2

$$\ln(a) = 1.38 + 0.55M - 0.68 \ln R + 0.32 I_s \qquad (4\text{-}16)$$

The magnitude used is assumed to be M_L.

Battis (1981) introduced a different approach for using intensity data to develop a relation between GMP and site intensity. Battis assumed that the radius of the felt area of earthquakes could be defined by a constant level of acceleration equal to 6 cm/sec^2. This value was based on his extrapolation of the results of Trifunac and Brady (1975).

Combined Models

To get the required relation between the GMP, magnitude, and distance applicable in the EUS, we must combine an intensity attenuation relation with an expression relating GMP to I_s. As outlined above, there are a number of

such combinations - each with their own assets and liabilities. The difference between the different intensity attenuation relations was illustrated in Fig. 4-2. To evaluate the difference between the various GMP-I_s relations we chose the modified Gupta-Nuttli curve shown in Fig. 4-2. It more or less represents an "average" between the different intensity attenuation relations. We combine the modified Gupta-Nuttli relation with Eqs. (4-3), (4-6) and (4-9) to develop three relations which approximately bound the different regression analysis results and assumptions. That is, we combine the different relations of the form

$$\ln(a) = C_1 + C_2\, I_s \tag{4-17}$$

with the modified Gupta-Nuttli relation

$$I_s - I_o = 3.2 - 0.0011R - 1.17\ \ln R \tag{4-18}$$

for $R \geq 15$ km

to obtain

$$\ln(a) = C_1 + C_2(I_o + 3.2 - 0.0011R - 1.17\ \ln R) \tag{4-19}$$

Figure 4-6 shows this comparison for epicentral intensities of V, VII and IX. This figure indicates that the choice of the GMP-I_s relation has an important effect on both the <u>rate of attenuation</u> and how the ground motion <u>scales</u> with earthquakes of larger epicentral intensity - both being controlled by the coefficient C_2 of the I_s term in Eq. (4-17). To a large extent the coefficient C_2 is controlled by what data is included or excluded in the lower intensity ranges.

To illustrate the impact of "unweighted", "distance weighted" and "magnitude weighted" relations, we have compared the results using the modified Gupta-Nuttli attenuation model with the GMP-I_s acceleration relations given by Eqs. (4-4), (4-13), and (4-15). We use this set because all three regressions were performed using approximately the same data base. In making the required substitutions, we obtain

$$\ln(a) = C_1 + C_3\ \ln R + C_4\, M_L + C_2\, [I_o + 3.2 - .0011R - 1.17\ \ln R] \tag{4-20}$$

where the coefficients C_i are obtained from the regression between site intensity and PGA.

A problem occurs here in making a comparison between Eq. (4-15) and either Eq. (4-13) or Eq. (4-4) because Eq. (4-15) uses M_L while the other two relations are in terms of epicentral intensity. Some relation must be used to translate M_L into the appropriate I_o in the EUS. This is normally done in a two

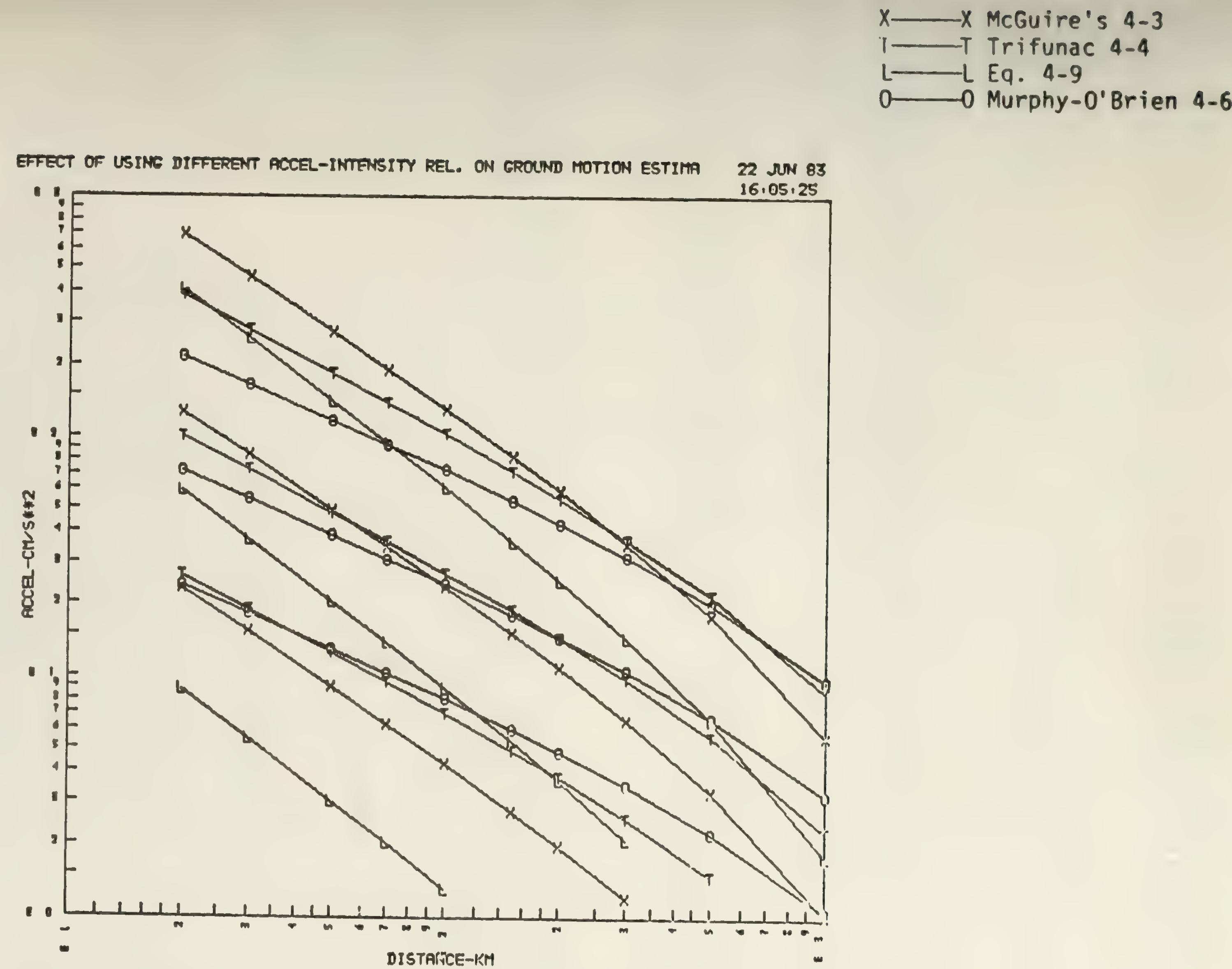


Fig. 4.6 Comparison of several combined models for intensities V, VII and IX.

step process. First the M_L is converted to an equivalent EUS m_{bLg} and then the m_{bLg} is converted to an equivalent I_o. As discussed earlier, it appears that

$$M_L \sim m_{bLg}$$

and in the past the relation

$$I_o = 2m_{bLg} - 3.5 \tag{4-21}$$

has been widely used in the EUS. Figure 4-7 shows the comparison of the unweighted, distance-weighted and magnitude-weighted models made by combining Eqs. (4-4), (4-13) and (4-15) with Eq. (4-18), the modified Gupta-Nuttli attenuation relation. In the distance-weighted model, the R in Eq. (4-13) is assumed to be the same as the R in Eq. (4-18). This, as discussed earlier, is not strictly true.

The last set of models we need to compare are the intensity based semi-empirical models. These models form a somewhat disjoint set. One of the earliest semi-empirical models was developed by Nuttli and Herrmann (1978). They combined the relation

$$I_s - I_o = 3.1 - 1.07 \ln R \tag{4-22}$$

which they felt approximates the Gupta-Nuttli relation, with Eqs. (4-16) and (4-21) and a free parameter. The use of Eq. (4-16) makes this essentially a "magnitude-and distance-weighted" approach. The free parameter was evaluated using judgment and available EUS data to obtain

$$\ln(a) = 1.47 + 1.2\, m_{bLg} - 1.02 \ln R;\ R > 15\ \text{km} \tag{4-23}$$

Battis (1981) assumed the model

$$\ln(a) = C_1 + C_2 M + C_3 \ln(R + 25) \tag{4-24}$$

M = appropriate magnitude scale
R = epicentral distance

To evaluate the coefficients in Eq. (4-24), Battis assumed that in the "near field" (i.e., R = 10 km) the ground motion is the same for all regions for the same epicentral intensity. In the "far field," at the limit of the felt area, he assumed that the ground motion is the same for all regions and sizes of earthquakes, using a value of 6 cm/sec^2. To obtain relations for both the central U.S. and the WUS, he used McGuire's (1974) relation to get PGA estimates at R = 10 km as a function of M_L. He used the relation between M_L and m_b derived by Brazee (1976) for California,

$$m_b = 1.28 + 0.75\, M_L, \tag{4-25}$$

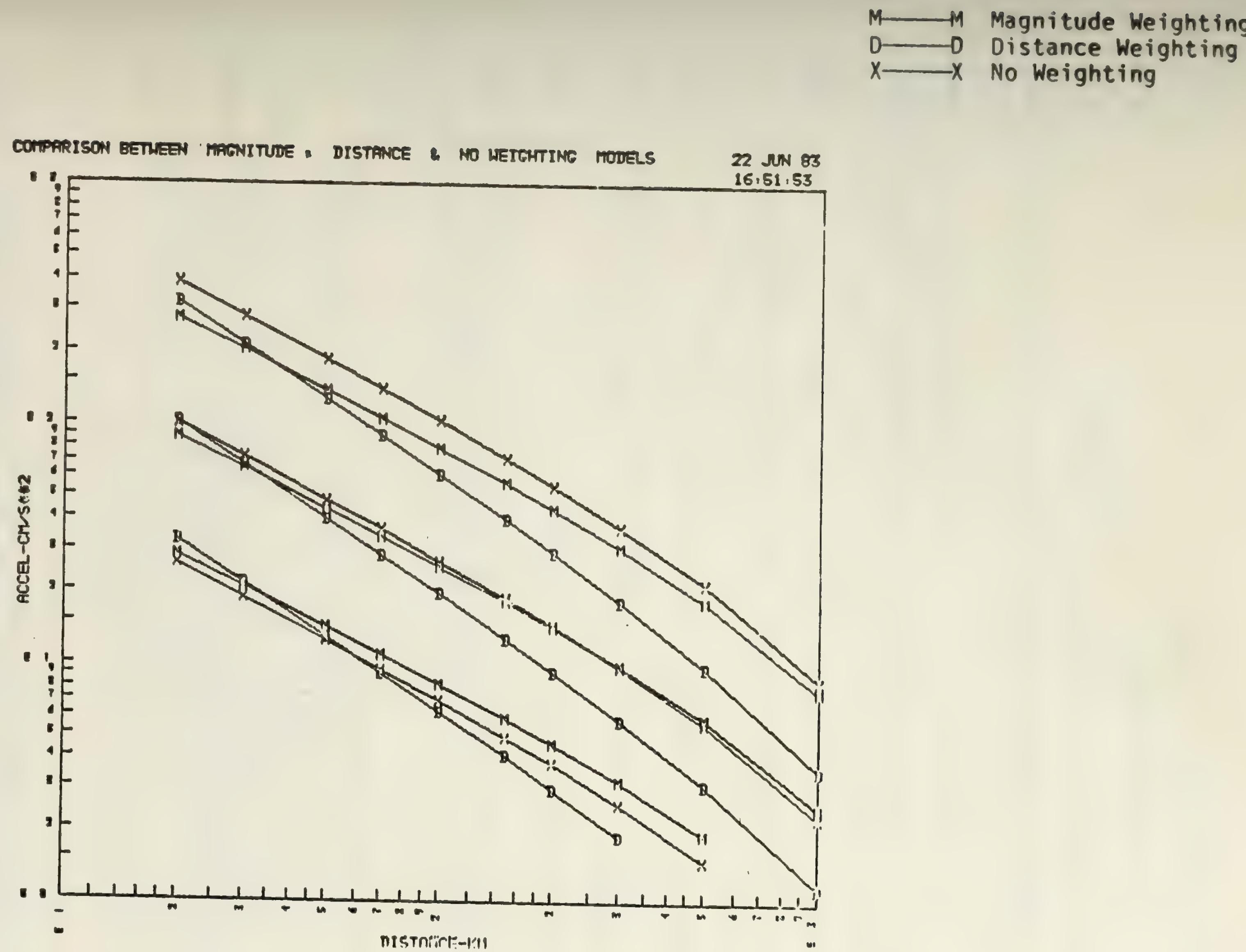


Fig. 4.7 Comparison of the magnitude weighted attenuation equations with the distance weighted and no weighting equations, for magnitudes 4.25, 5.25, and 6.25 (i.e., approximately source intensity $I_o \sim$ V, VII and IX).

and Brazee's relation between m_b and I_o,

$$m_b = 2.89 + 0.37\ I_o, \tag{4-26}$$

to relate the parameters M_L, m_b and I_o for the WUS.

Battis developed an approximate relation for the radius of felt area for the WUS. For the Central U.S., he used the relation

$$m_b = 2.6 + 0.34\ I_o \tag{4-27}$$

and determined the distance of the felt area using Nuttli and Zolweg's (1974) relation between the felt area and m_b

$$\ln R_f = -6.23 + 3.41\ m_b - 0.2\ m_b^2 \tag{4-28}$$

He evaluted the coefficients of Eq. (4-24) using a least squares process and obtained

$$\ln(a) = 3.16 + 1.24\ m_b - 1.24\ \ln(R + 25) \tag{4-29}$$

for the Central US. Fig. 4-8, taken from Battis, compares Eq. (4-29) to his result for the WUS,

$$\ln(a) = 5.83 + 1.21\ m_b - 2.08\ \ln(R + 25) \tag{4-30}$$

At 10 km the difference between Eqs. (4-29) and (4-30) arises because of the differences between Eqs. (4-26) and Eq. (4-27). For example at I_o = VII Eq. (4-26) results in m_b values that are about 0.5 units larger than those given by Eq. (4-27).

Weston Geophysical Corporation, Inc. (WGC) has proposed a model for New England. WGC based the attenuation of intensity on four New England earthquakes ranging in magnitude from 3.5 to 5.8. WGC used Eq. (4-11) (distance weighting) to convert from site intensity to ground motion. They noted that because of the small range of magnitudes of the earthquakes involved that the scaling with magnitude determined by the regression analysis was unreliable. To account for this, they changed the coefficient of m_b from the value of 0.7 determined from the regression to 1.1 and readjusted the constant so that the model with the 1.1 slope agreed with the 0.7 slope model at $m_b = 4.875$. Their resultant model is given by

$$\ln(a) = 1.47 + 1.1\ m_b - 0.88\ \ln R - 0.0017R \tag{4-31}$$

The Nuttli-Herrmann model, Eq. (4-23), the Battis model, Eq. (4-29), and the WGC model, Eq. (4-31), are compared in Fig. 4-9. Also shown in Fig. 4-9 for comparison is the magnitude-weighted model, Eqs. (4-15) and (4-20) expressed in terms of m_b through Eq. (4-21),

$$\ln(a) = 0.77 + 1.13\ m_b - 0.0007R - 0.74\ \ln R \tag{4-32}$$

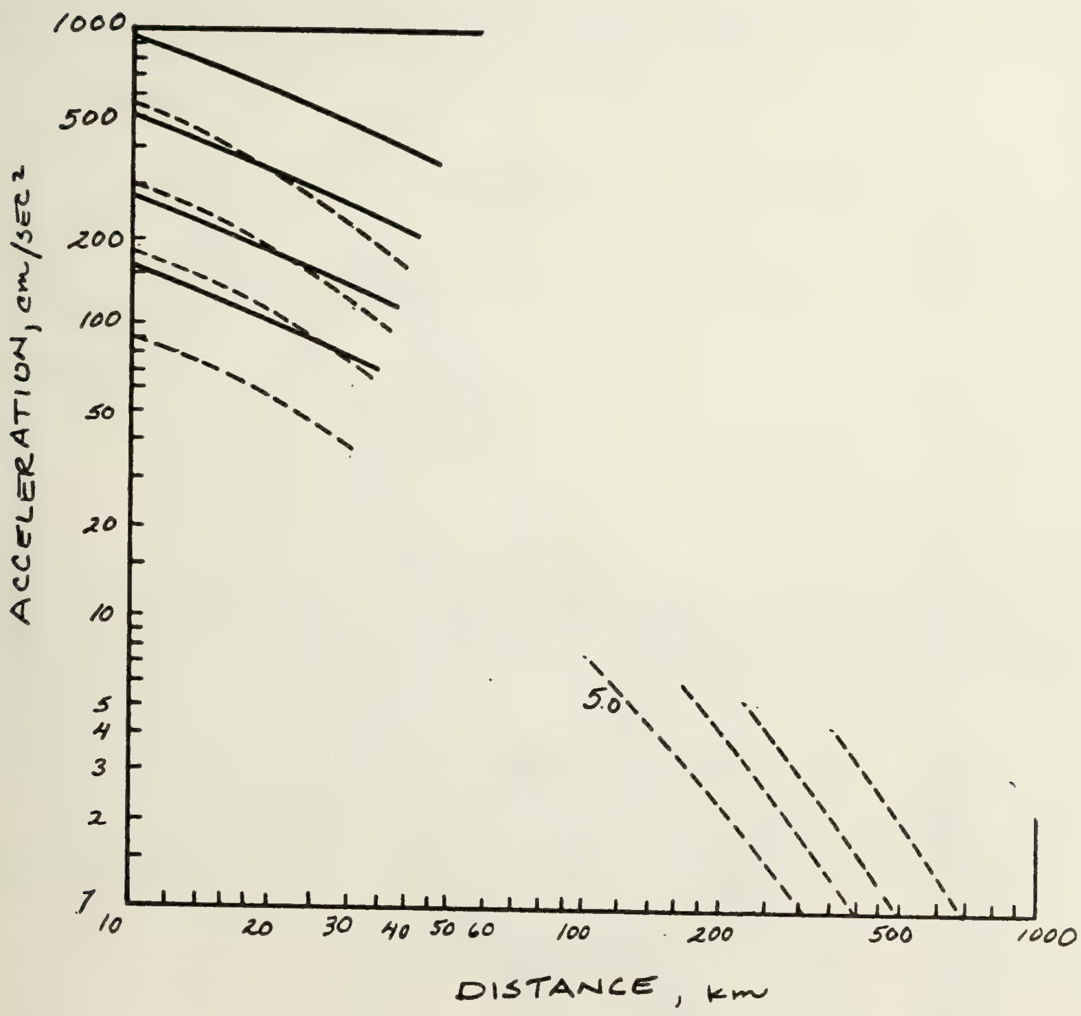


Figure. 4.8 Comparison of derived peak acceleration attenuation functions for the Central United States (solid curves) and California (dashed curves). Battis's Model.

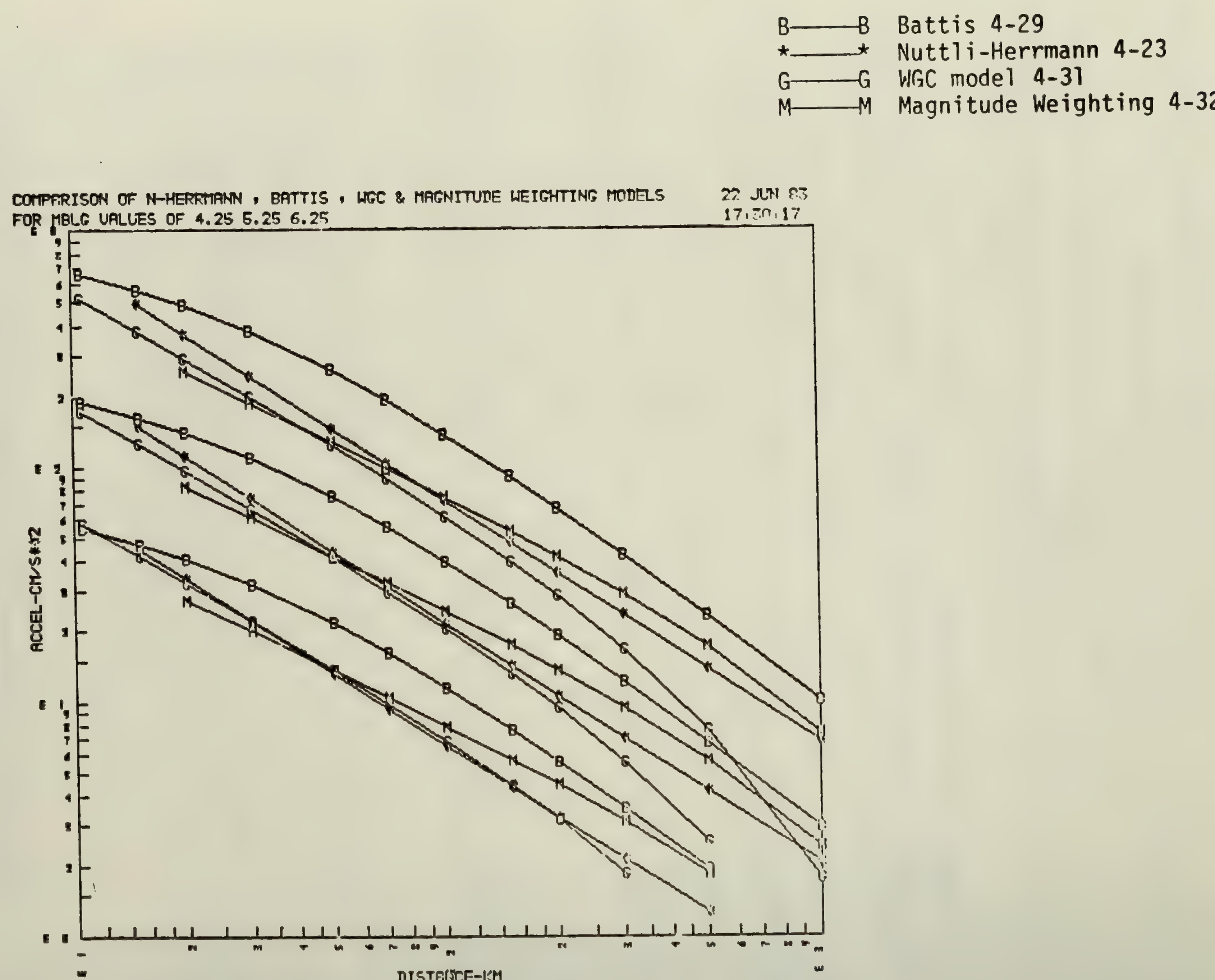


Fig. 4.9 Comparison of the magnitude weighting mdoel (M, Eq. 4-39) with Battis' model (B, Eq. 4-29), the Nuttli-Herrmann model (*, Eq. 4-23) and the Weston Geophysical model (G, Eq. 4-31).

4.2 Direct Models

Although there are many possible models in the categories referred to as D-1 and D-2, in fact, only a few have been formally developed. Recall that category D-1 includes those semi-empirical models that do not use site intensity as an intermediate variable and assume that differences between the ground motion from EUS and WUS earthquakes are only related to the differences in attenuation between the two regions. Category D-2 includes those models which assume that in addition to attenuation differences between the two regions there are also differences in magnitude scaling.

Nuttli (1979) assumes that

$$GMP\ (R) = A_o R^{-5/6} \exp(-\gamma R) \qquad (4\text{-}33)$$

where γ is a regional absorption coefficient. Eq. (4-33) is a theoretical attenuation curve for Lg waves.

Nuttli further assumes that

$$\log A_{max} \propto 0.5 m_b$$

$$\log V_{max} \propto 1.0 m_b\ .$$

In addition, he assumes that the source spectra of EUS earthquakes are the same as for WUS earthquakes, so that the ground motions observed in the near-source region are the same for both areas. Nuttli also assumes that the predominate frequency of the ground motion for identical magnitude earthquakes is the same between the two regions.

The constant A_o in Eq. (4-33) was assumed to be proportional to m_b as given in the above relations and calibrated using the San Fernando earthquake. The appropriate absorption coefficient for the central US was taken from Nuttli and Dwyer (1978). Nuttli's (1979) model is given by the following equations:

$$\ln(a) = 1.481 + 1.15\ m_b - \gamma R - 5/6\ \ln(R) \qquad (4\text{-}34)$$

$$\text{where } \gamma = 0.0136 - 0.00172\ m_b$$

In addition to Nuttli's (1979) model we are aware of four other models that fall into category D-1, one that we developed for SSMRP, Campbell's (1981b) and (1982) models, and the model used by Algermissen and Perkins (1976). We exclude the model by Algermissen and Perkins because it is nonanalytical and would be difficult to use in the hazard analysis. The model is based on the relation of Schnabel and Seed (1973) with a regional correction for attenuation. Figure 4-10 taken from Algermissen et al. (1982) compares this model to that of Nuttli and Herrmann (1981). Aglermissen et al. do not indicate what relation they used to go from m_b to M_s.

In developing the SSMRP model we started with Nuttli's (1979) suggestion that

$$GMP = A_o(m_b)\ R^{-5/6}\ \exp(-\gamma\ R) \tag{4-35}$$

Nuttli suggested that $A_o(m_b)$ could be determined from WUS data using the assumption that the only difference between WUS and EUS earthquakes is a difference in regional attenuation. To develop the SSMRP model we repeated the regression analysis on the data set of Joyner and Boore (1981) ($M_L \geq 5.0$) using an approach similar to theirs. However, in our analysis the coefficient of geometrical attenuation was taken to be -5/6 (in agreement with Nuttli's model) rather than the value of -1 assumed by Joyner and Boore. The purpose of this change was to put the model in the same form as assumed by Nuttli when he determined the regional absorption coefficients for the EUS and WUS. In addition, a value of m_b appropriate for the EUS (or an estimate of this value) was used for the measure of the size of the earthquakes. We determined the best fit relation

$$\ln(a) = 3.99 + 0.59\ m_b - 5/6\ \ln R - 0.007R \tag{4-36}$$

where

$$R^2 = [d^2 + h^2]^{1/2}$$
$$h = 5.3$$

and d is the shortest distance between the site and the surface projection of the fault rupture plane.

Nuttli (1979) obtained a similar estimate for γ in the WUS. For the central U.S. (CUS) Nuttli (1982) estimates $\gamma = 0.003$. If indeed the ground motion from CUS earthquakes scales the same with magnitude as WUS earthquakes, we can convert the above relation into a CUS ground motion model simply by replacing γ with an appropriate value for the CUS. This gives

$$\ln(a) = 3.99 + 0.59\ m_b - 5/6\ \ln R - 0.003\ R \tag{4-37}$$

where

$$R^2 = [d^2 + h^2]^{1/2}$$
$$h = 5.3$$

Campbell (1981b) uses a different functional form than that used by Nuttli (1979) or Joyner and Boore (1981). He takes as his relationship for modeling the attenuation of peak acceleration with distance the expression

$$\ln(a) = a + bM - d\ \ln[R + C(M)] - \gamma R \tag{4-38}$$

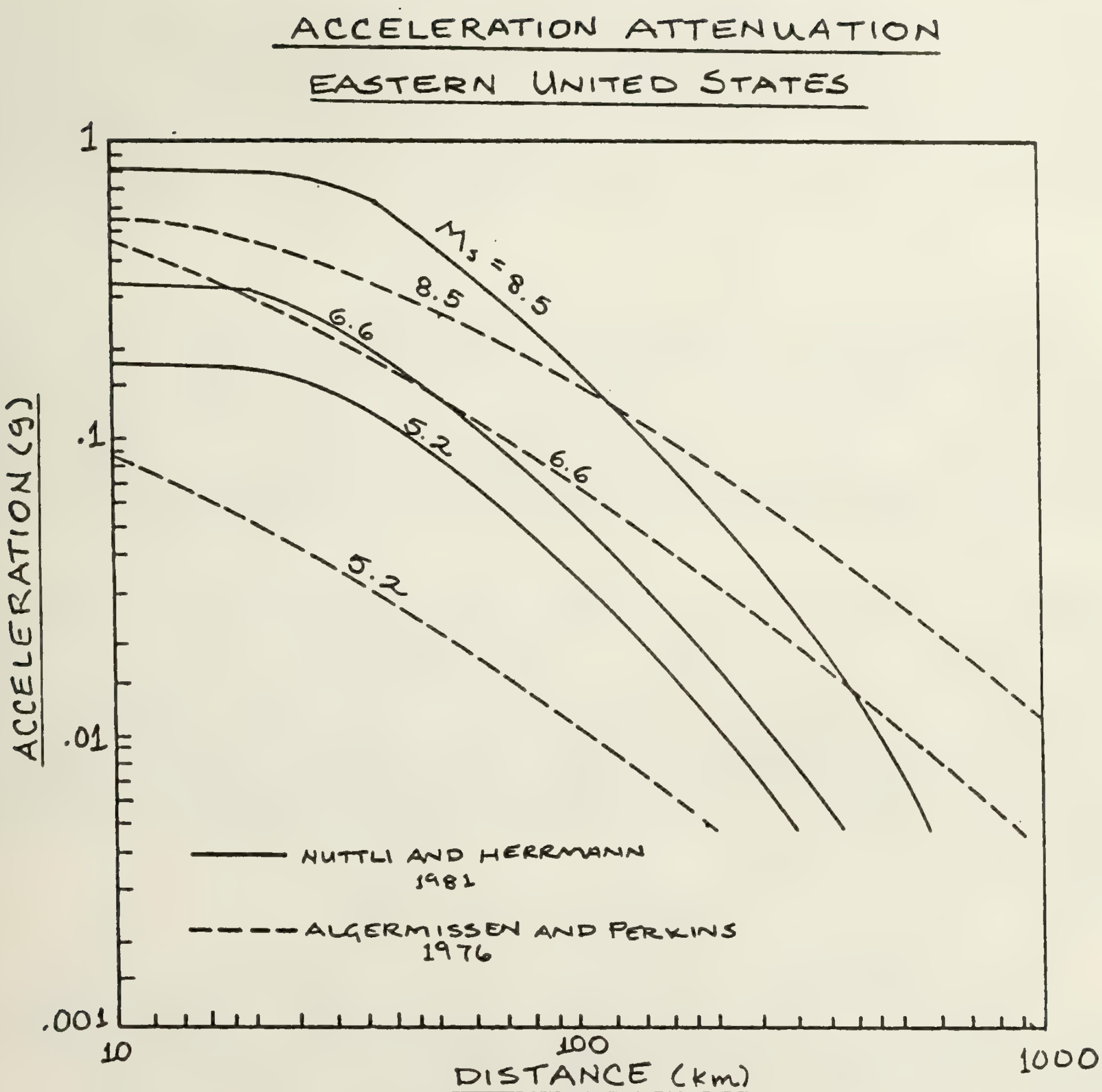


Figure 4.10 Comparison of Algermissen and Perkins (1976) and Nuttli and Herrmann (1981) Acceleration Attenuation Curves for the Eastern and Central United States.

Campbell selected this functional form because it is capable of modeling nonlinear magnitude and distance scaling effects in the near field that may be supported by the data. The far-field properties of this relationship are characterized by the coefficient b which controls magnitude scaling, the coefficient d which controls the geometrical attenuation rate, and the coefficient γ which controls the rate of attenuation due to absorption.

C(M) modulates the attenuation of acceleration at distances close to the source where little geometrical attenuation is expected (Hadley and Helmberger, 1980). Since the distance at which the transition from far-field to near-field attenuation occurs is probably proportional to the size of the fault rupture zone, and since fault rupture dimensions scale exponentially with magnitude, Campbell used the following relationship to model C(M):

$$C(M) = C_1 \exp(C_2 M) \qquad (4\text{-}39)$$

Eq. (4-38) differs from Nuttli's relationship (Eq. 4-34) in two ways. The first is that the geometrical attenuation term d is not fixed but rather was determined from the regression analysis. The second is the addition of the C(M) parameter. Both of these differences are required to accommodate the near-source effects of extended fault rupture in the case of large earthquakes and accommodate the depth of the source in the case of small events.

He based his analysis on the near-source data base of Campbell (1981a). Earthquakes were selected only if their magnitude was equal to or greater than 5.0. Distances were restricted to be no further than 30 km from the fault rupture plane for $5.0 \leq M < 6.25$ and no further than 50 km from the fault for $M \geq 6.25$. Analyses were conducted separately for two definitions of distance: the closest distance to the fault rupture surface, referred to as fault distance, and epicentral distance. He considered peak acceleration to be regionally invariant at the source (i.e., at R = 0). He used the values of absorption proposed by Nuttli (1979) in the WUS to establish γ, from which he developed the relation

$$\gamma_{WUS} = 0.042 - 0.009M + 0.00057M^2 \qquad (4\text{-}40)$$

Using a weighted regression analysis similar to that of Campbell (1981a) he found the following expression for the median (50th-percentile) value of peak acceleration in cm/s^2 in terms of <u>fault distance</u>:

$$\ln(a) = 2.64 + 0.79M - 0.862 \ln [R + 0.0286 \exp(0.778M)] - \gamma R \qquad (4\text{-}41)$$

with a standard error of ln(a) of 0.409.

The results of the regression analysis for <u>epicentral distance</u> yielded the following expression for the median value of peak acceleration:

$$\ln(a) = 4.39 + 0.922M - 1.27 \ln [R + 25.7] - \gamma R \qquad (4\text{-}42)$$

where C_2 was found to be equal to zero. The standard error of ln(a) was found to be 0.548.

Since the standard measure for earthquake size in the CUS is m_b, Campbell's application of Eqs. (4-41) and (4-42) to this region required a conversion from m_b to M, the magnitude scale used in the development of these relationships. The magnitude scale used in the above equations was defined as M_s when both M_s and M_L were larger than 6.0 and M_L when both were below this value. Campbell used the relationships between magnitude scales developed by Nuttli (1979) and his definition of M to develop the following conversion relation

$$M = \begin{cases} 1.64\ m_b - 3.16 & (m_b \geq 5.59) \\ 1.02\ m_b + 0.30 & (m_b < 5.59) \end{cases} \tag{4-43}$$

An appropriate ground motion model for the CUS was obtained by substituting values of γ for the CUS proposed by Nuttli (1979) using the expression

$$\gamma_{CUS} = 0.023 - 0.0048M + 0.00028\ M^2 \tag{4-44}$$

This analysis was later revised by Campbell (1982) using a frequency dependent expression for γ of the form

$$\gamma = \frac{\pi T^{\eta}}{Q_o T_o^{\eta} T U} \tag{4-45}$$

where T is the period of the wave, U is the group velocity, Q_o is a reference value for the quality factor Q, T_o is a reference value for period, and η is defined by the expression

$$Q = Q_o \left(\frac{T_o}{T}\right)^{\eta} \tag{4-46}$$

The predominant period of PGA for sites located on rock was modified from a plot given by Seed et al. (1969), resulting in the relation

$$T = \begin{cases} -0.229 + 0.0650M + (0.000556M - 0.00172)R & (M \geq 7.0) \\ -0.043 + 0.0382M + (0.000556M - 0.00172)R & (M < 7.0) \end{cases} \tag{4-47}$$

An expression for γ appropriate for California was obtained by substituting the values $Q_o = 150$, $\eta = 0.55$, $U = 3.5$ km/sec and $T_o = 1$ sec. into Eq. (4-45) based on the regionalization of Q for the United States by Singh and Herrmann (1983). Using this expressionfor γ and the relation for period given by Eq. (4-47), the analysis of Campbell (1981b) was revised, resulting in the following expression for peak acceleration (g):

$$\ln(a) = -4.290 + 0.777M - 0.797\ \ln[R + 0.012\ \exp(0.898M)] - \gamma R \tag{4-48}$$

where R is fault distance as defined previously. The standard error for ln(a) in this analysis was 0.405.

While Campbell only applied Eq. (4-48) to the estimation of PGA in the northcentral Utah region, this expression may be applied to other regions of the U.S. by selecting an appropriate value for Q_o and η from Singh and Herrmann (1983) (or some other source if appropriate) and selecting an appropriate value or relation for the predominant period of PGA. Then γ may be estimated from Eq. (4-45) and substituted into Eq. (4-48) to estimate PGA. A conversion between M and m_b may be taken from Eq. (4-43) or from more current relations proposed by Nuttli (1983 a,b).

Figure 4-11 compares Campbell's Eqs. (4-41) and (4-42) and the SSMRP model given by Eq. (4-37) for an m_b of 4.25, 5.25, and 6.25. In making this plot several items need to be noted. First, Eq. (4.37) is plotted as a function of the distance R. This is consistent with the distance R in Eq. (4-38) for EUS earthquakes where earthquakes do not rupture to the surface. In Fig. 4-11 the epicentral distance R in Eq. (4-42) is different than either of the other two definitions, but it is plotted as R for reference. For a discussion of the differences in the definition of distance as it relates to the prediction of strong ground motion, the reader is referred to Appendices B and C and Shakal and Bernreuter (1981). Second, it should be noted that we have extrapolated beyond the data to plot the curves for m_b = 4.25. However, as an extended data set is not readily available, it is not possible at this time to revise these models using smaller magnitude data. At some point in your response to us you should note if it is necessary for us to extend these models.

As can be seen from Fig 4-11 there is a considerable difference between all three models. One notable difference is how the ground motion scales with magnitude. For Eqs. (4-41) and (4-42) the m_b was converted to the magnitude M used by Campbell based on Eq. (4-43).

This is believed to contribute to the differences in the magnitude scaling properties of Eq. (4-37) and Eqs. (4-41) and (4-42). In the SSMRP model it was assumed that $M_L = m_{bLg}$, whereas for the Campbell models M was determined using the magnitude conversion relations developed by Nuttli (1979) resulting in an m_b approximately 0.3 to 0.4 units smaller than M_L. In order to see what impact this might have on the results we replot Campbell's models on Fig. 4-12 using M = m_b (Note: this is only strictly valid for M < 6.0 where M = M_L). As seen from Fig. 4-12 the scaling of PGA with magnitude is still significantly different between all three models. We may conclude from these comparisons that the relations used to convert between scales is an important consideration in the development of a ground motion model in the EUS.

We only know of one model that falls into Category D-2. This is the latest version of the model of Dr. Nuttli and is part of a long developmental process. Appendix C-A gives the details of the model and some other reflections on the questions before this panel by Dr. Nuttli. Figure 4-13 compares Nuttli's (App. C-A) model with his 1979 model given by Eq. (4-34).

E——E Campbell's Epicentral Model (4-41)
C——C Campbell's Closest Approach (4-42)
—— SSMRP Model (4-35)

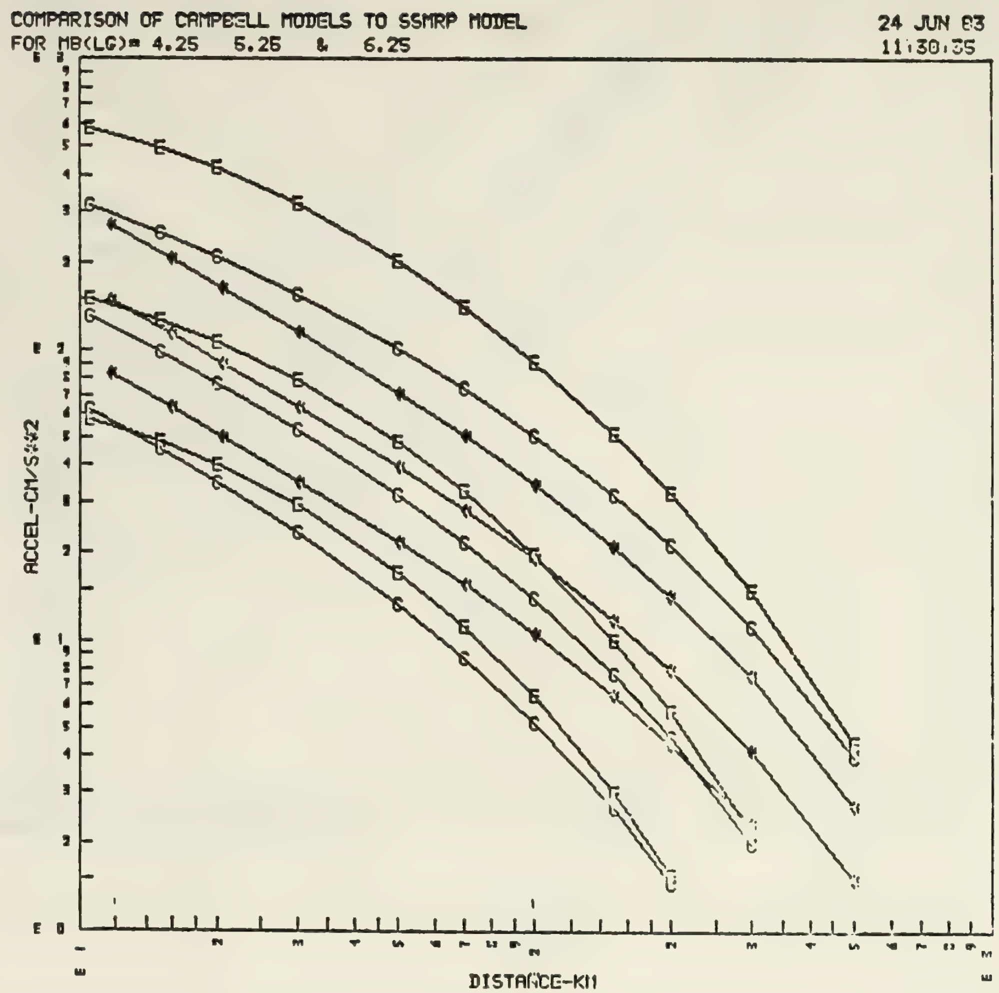


Fig. 4.11 Comparison of Campbell models to SSMRP model.

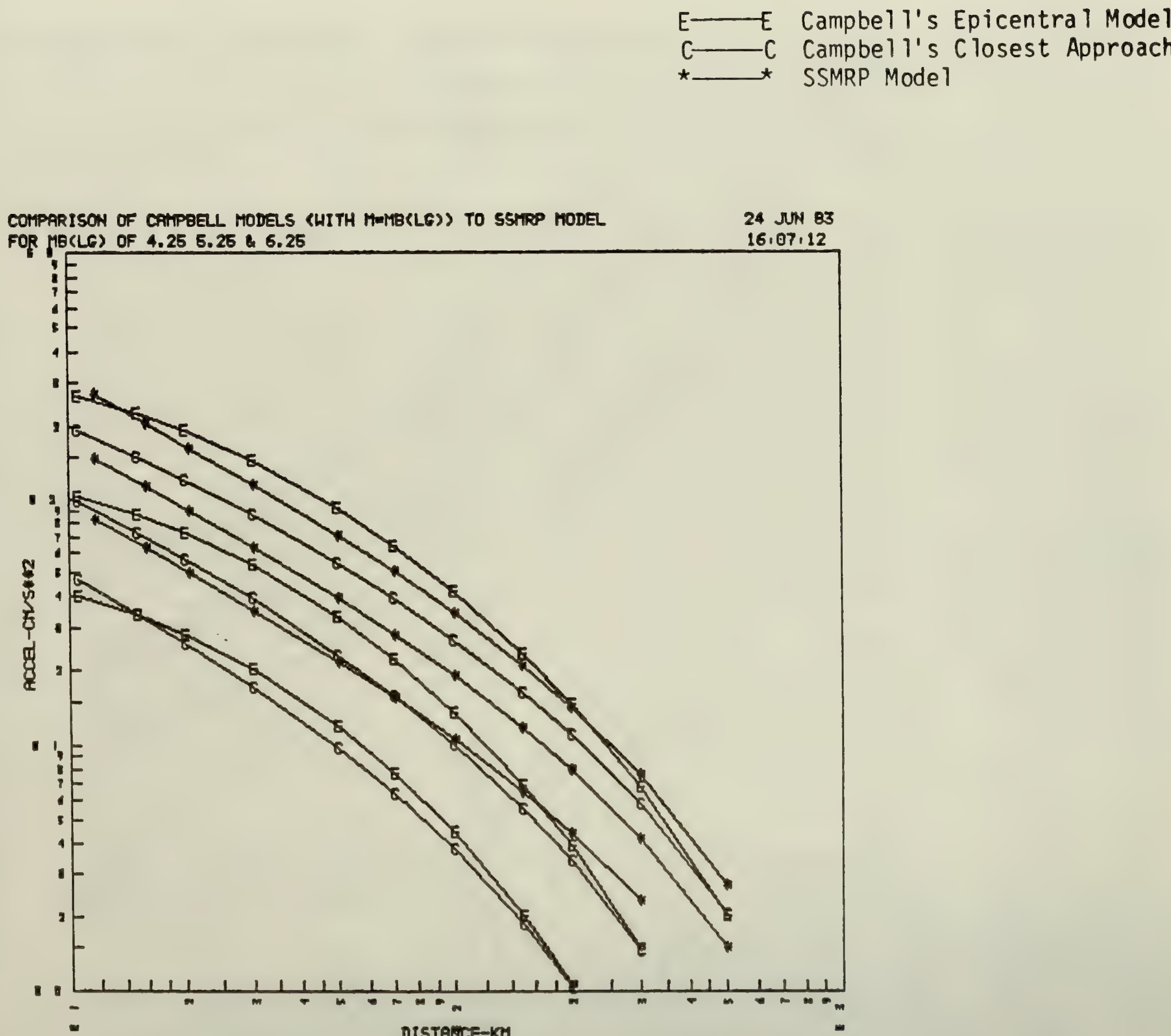


Fig. 4.12 Comparison of Campbell models to SSMRP model.

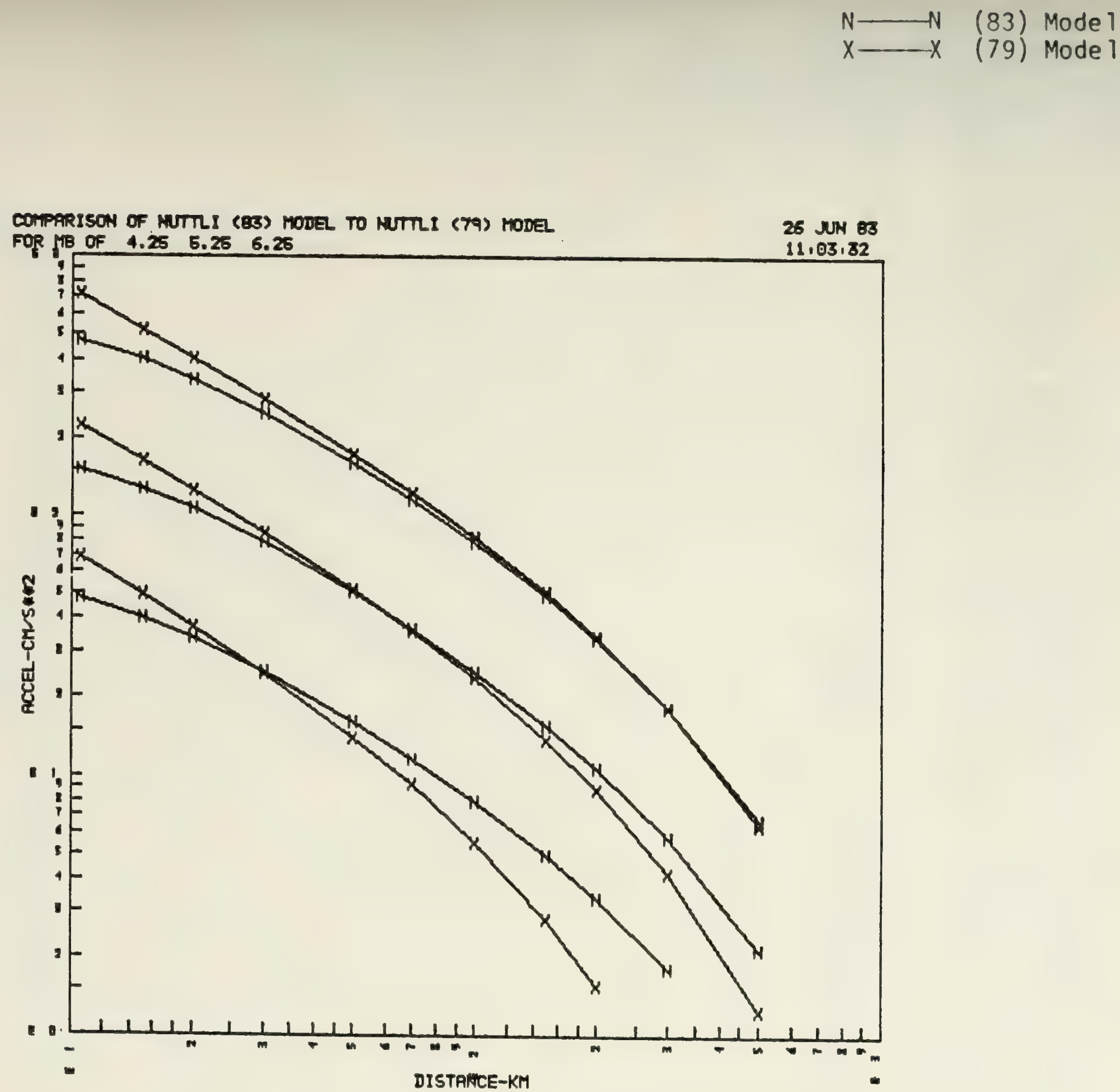


Fig. 4.13 Comparison of Nuttli model (83) to (79) model.

To make this plot we assume a depth of $h = 12$ km in his App. C-A model and take the distance R in both models to be the same. The models are found to be very similar--the differences arise primarily from the inclusion of the depth term and the change to a constant value for anelastic attenuation in the App. C-A model.

Figure 4-14 compares Campbell's epicentral model, Eq. (4-42), the SSMRP model, Eq. (4-37), Nuttli's App. C-A model and the Intensity Based Magnitude-Weighted Model, Eq. (4-32). The models of Campbell and Nuttli are very similar, except for differences in anelastic attenuation at the smaller magnitudes. The SSMRP model exhibits substantially less magnitude scaling and the magnitude-weighted model exhibits substantially less attenuation than the other models.

To facilitate making additional comparisons we have provided you with clear overlays of several of the key figures.

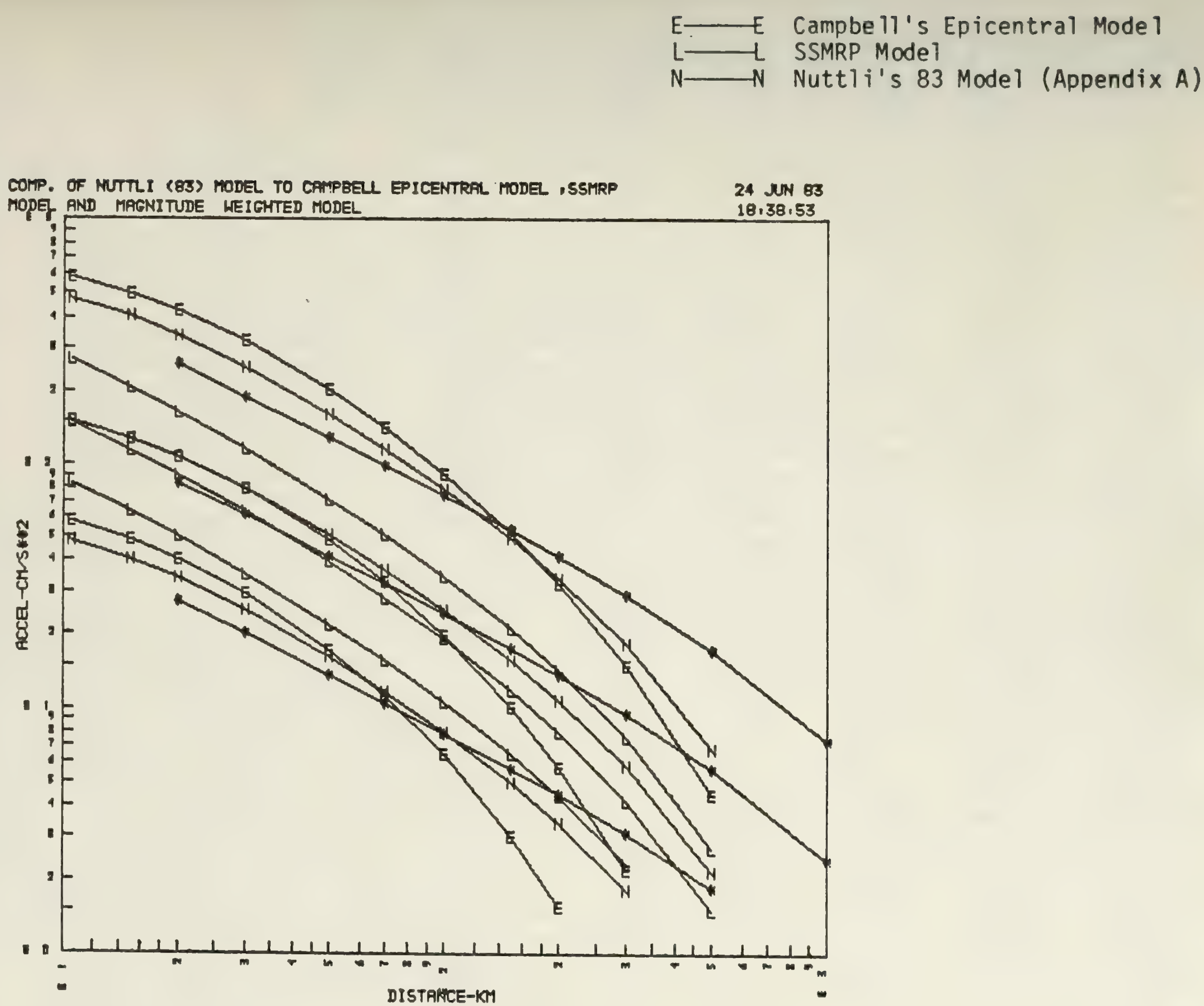


Fig. 4.14 Comparison of Campbell's epicentral model, SSMRP model and magnitude weighted model.

5.0 REVIEW OF VELOCITY AND SPECTRAL MODELS

Only a few of the investigators referenced in Section 4 have developed scaling relationships for peak velocity and response spectral ordinates. This creates a dilemma, since it is the probabilistic prediction of response spectra that is ultimately required for the characterization of seismic hazards in the EUS.

Since a discussion of peak velocity relations would be very similar to the previous discussion on peak acceleration, no presentation of actual models will be made here. Rather, the reader may refer to the Questionnaire Section 7 for a list of available models.

Of all the investigations referred to in Section 4, only three present models for response spectral ordinates. Two of these, the "distance-weighted" and "magnitude-weighted" intensity models of Bernreuter (1981b), were developed for the previous SEP study. The only other available model is a "no-weighted" intensity model based on the approach taken by Trifunac and Brady (1975) to develop similar relations for peak ground motion parameters. Because of the importance of response spectra, we feel it necessary to augment these limited models with models based on standard response spectral shapes.

Three spectral shapes will be considered; these are (1) the shape recommended by the Nuclear Regulatory Commission for the seismic design of Nuclear Power Plants (USAEC, 1973), (2) the shape recommended by the Applied Technology Council for the seismic design of buildings (NBS, 1978), and (3) the shape recommended by Newmark and Hall (1982) for the seismic design of all types of buildings (although originally developed for the design of nuclear power plants). While other spectral shape models exist, these three comprise those commonly used in practice. Of course, if you feel another model should be considered, you may indicate so in the Questionnaire. The following is a brief discussion of each model.

5.1 Nuclear Regulatory Commission

The response spectral shape recommended by the Nuclear Regulatory Commission (NRC) for the design of nuclear power plants is described in U. S. Atomic Energy Commission Regulatory guide 1.60 (USAEC, 1973). This shape is based on a statistical analysis of response spectra of strong-motion earthquakes as described by Newmark et al. (1973a). It is a broad-band spectrum, encompassing earthquakes of various sizes and distances. The NRC regulatory staff has determined this shape to be acceptable for defining the Design Response Spectra representing the effects of the vibratory motion of the Safe Shutdown Earthquake (SSE), one-half the SSE, and the Operating Basis Earthquake (OBE) for sites underlain by either rock or soil deposits and covering all frequencies of interest. They further indicate that this shape should not be used for sites that are relatively close to the epicenter of an expected earthquake or have physical characteristics that could significantly affect the spectral pattern of input motion, such as being underlain by poor soil deposits.

The spectrum shape recommended in Regulatory Guide 1.60 was selected to represent an 84th percentile spectrum when anchored to a median value of PGA. This makes this spectrum incompatible with the requirements of our project, which is designed to estimate a median or "best estimate" spectrum for a given probability of exceedance and to specify appropriate confidence limits. The 50th percentile (median) spectral shape consistent with Regulatory Guide 1.60 was obtained from Newmark et al. (1973a). To meet the program objectives the median amplification factors for each frequency control point was estimated from the ratio of the 84.1% and 50% amplification factors given in the original studies used to establish the amplification factors for each control point. This resulted in 5%-damped median amplification factors that are 23% and 26% lower in the acceleration domain (control points at 9 Hz and 2.5 Hz, respectively) and 31% lower in the displacement domain (control point at 0.25 Hz) than the corresponding 84.1% amplification factors. This median spectral shape will be referred to as the Modified Regulatory Guide 1.60 spectrum.

The spectrum based on an 84th percentile shape is shown in Fig. 5.1 for damping values of 0.5, 2, 5, 7 and 10% and a peak horizontal acceleration of 1g. The spectrum may be adjusted to any other value of PGA by linearly scaling Fig. 5-1 in proportion to the desired value of peak acceleration. Thus, the shape remains independent of magnitude, distance, and site characteristics. The applicable amplification factors and control points used to construct the spectrum for a specified PGA is given in Table 5-1.

5.2 Applied Technology Council

The response spectral shapes recommended by the Applied Technology Council (ATC) for the seismic design of buildings is described in National Bureau of Standards Special Publication 510 (NBS, 1978). Spectral shapes representative of different soil conditions were selected on the basis of a statistical study of the spectral shapes developed on such soils close to the seismic source zone in past earthquakes (Seed et al., 1976; Hayashi et al., 1971). They represent smoothed spectral shapes for the following three soil profiles.

Soil Profile Type S_1: Rock of any characteristic, either shale-like or crystalline in nature (such material may be characterized by a shear wave velocity greater than 2500 ft/sec); or stiff soil conditions where the soil depth is less than 200 ft and the soil types overlying rock are stable deposits of sand, gravels, or stiffer clays.

Soil Profile Type S_2: Deep cohesionless or stiff clay soil conditions, including sites where the soil depth exceeds 200 ft and the soil types overlying rock are stable deposits of sands, gravels, or stiff clays.

Soil Profile Type S_3: Soft-to-medium stiff clays and sands, characterized by 30 ft or more of soft-to-medium-stiff clay with or without intervening layers of sand or other cohesionless soils.

TABLE 5-1

SPECTRUM AMPLIFICATION FACTORS FOR HORIZONTAL

ELASTIC RESPONSE

(Taken in Part from Newmark et al., 1973 a)

Damping % Critical	One Sigma (84.1%) Accel. 33 Hz	One Sigma (84.1%) Accel. 9 Hz	One Sigma (84.1%) Accel. 2.5Hz	One Sigma (84.1%) Displ. 0.25 Hz	Median (50%) Accel. 33 Hz	Median (50%) Accel. 9 Hz	Median (50%) Accel. 2.5 Hz	Median (50%) Displ. 0.25 Hz
0.5	1.0	4.96	5.95	3.20	1.0	3.11	3.84	2.11
2.0	1.0	3.54	4.25	2.50	1.0	2.53	2.93	1.67
5.0	1.0	2.61	3.13	2.05	1.0	2.01	2.32	1.41
7.0	1.0	2.27	2.72	1.88	1.0	1.91	2.09	1.32
10.0	1.0	1.90	2.28	1.70	1.0	1.62	1.73	1.21

Note: Maximum ground displacement is taken proportional to maximum ground acceleration, and is 36 in. for ground acceleration of 1g.

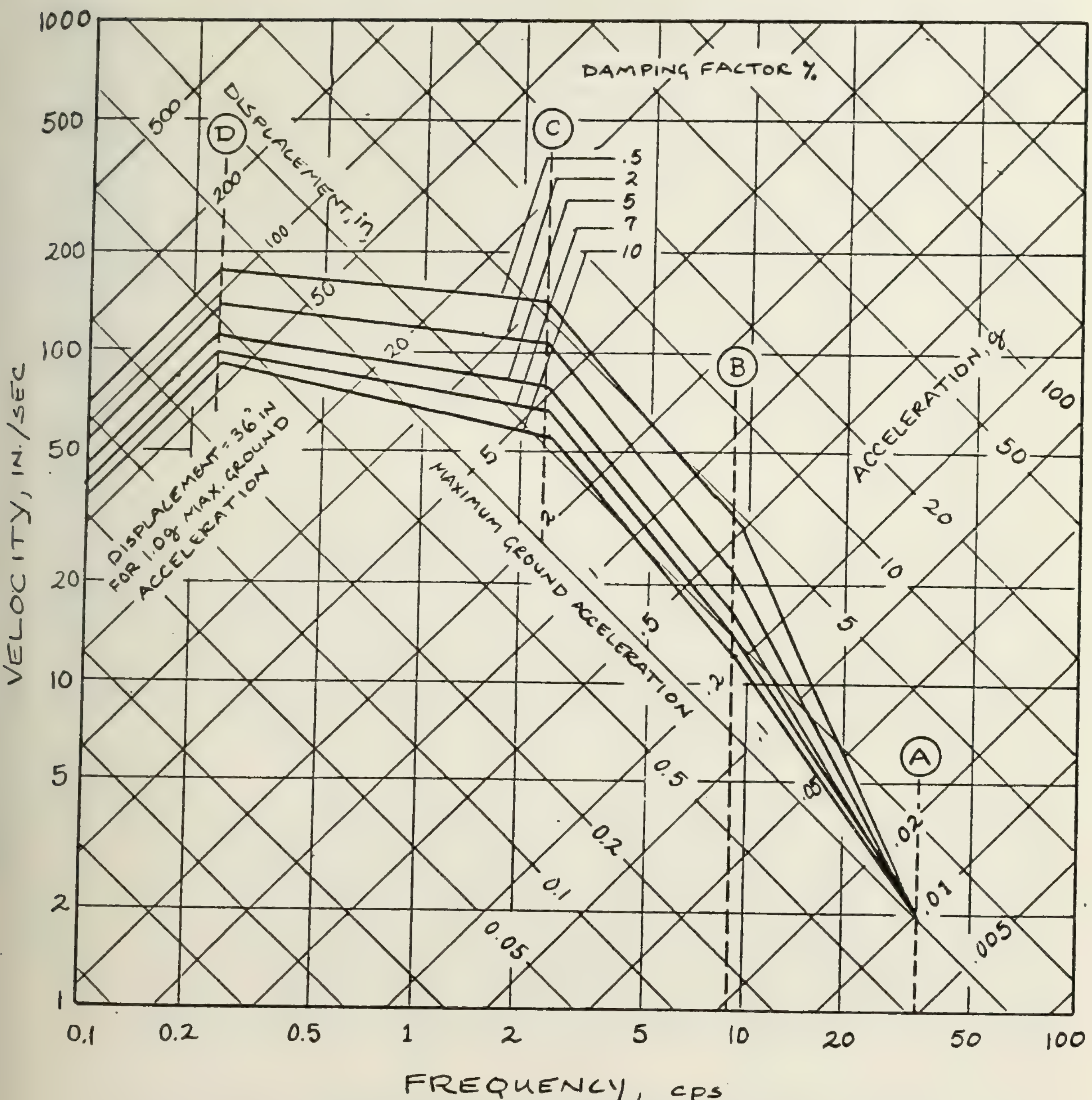


FIGURE 5-1. Horizontal design response spectra-scaled to 1g horizontal ground acceleration (USAEC, 1973).

The spectral shapes are used by ATC in conjunction with two indeces - A_a, a parameter numerically equal to Effective Peak Acceleration (specified in units of g), and A_v, a parameter related to Effective Peak Velocity--in defining a design response spectrum. However, the similarity of the spectral shapes to those recommended by Seed et al. (1976) suggests that they may be used in conjunction with PGA to adequately represent ground motion spectra for use in our project. Spectra for an Effective Peak Acceleration of 0.4g (A_a=0.4) and 5% damping are shown in Fig. 5.2. The value of A_a for Soil Profile Type S_3 has been reduced by 20% as recommended by ATC. This would not be required when anchoring the spectral shapes to PGA, as this parameter would already contain the effects of site characteristics. The spectra may be adjusted to any other value of A_a or PGA by linearly scaling Fig. 5-2 in proportion to the desired value of acceleration. However, for relatively large distances where $A_v > A_a$, ATC recommends that the velocity portion of the spectra (the horizontal portion in Fig. 5-2) be multiplied by the ratio of A_v to A_a and the remainder of the spectra extended to maintain the same overall form. This takes into account the change in spectral shape that has been observed to occur at large distances. However, the shapes remain independent of earthquake magnitude.

5.3 Newmark-Hall

The response spectral shapes recommended by Newark and Hall for the seismic design of buildings is described in a Monograph published by The Earthquake Engineering Research Institute (Newmark and Hall, 1982). The development of these shapes has been an evolutionary process, but has been primarily based on the statistical studies of Newmark et al. (1973 b), Hall et al., (1976) and Newmark and Hall (1978). They recommend that appropriate regions of the spectra be scaled by peak acceleration, peak velocity, and peak displacement. This enables the shape to vary with magnitude, distance, and site characteristics in accordance with the variation in these peak parameters.

While Newmark and Hall give amplification factors for both median and 84th percentile shapes, the median values are of interest in our study. Table 5-2 presents these amplification factors for various values of damping. The factors labeled A, V and D represent amplification factors based on peak acceleration, peak velocity and peak displacement, respectively. These domains are defined in fig. 5-3 which gives the 84th percentile, 5%-damped spectrum for a peak acceleration of 0.5g, a peak velocity of 61 cm/sec, and a peak displacement of 45 cm. The corresponding median spectrum would be reduced by 22% in the acceleration domain (A), 28% in the velocity domain (V), and 31% in the displacement domain (D) with respect to the 84th percentile spectrum.

Newmark and Hall recommend that, lacking other information, values of peak velocity (v) may be estimated from peak acceleration (a) by taking a v/a ratio of 48 in/sec/g for competent soil conditions and a v/a ratio of 36 in/sec/g for rock. Peak displacement (d) may be estimated by taking the ratio ad/v^2 to equal about 6.0. The recommendation concerning v/a will be followed when

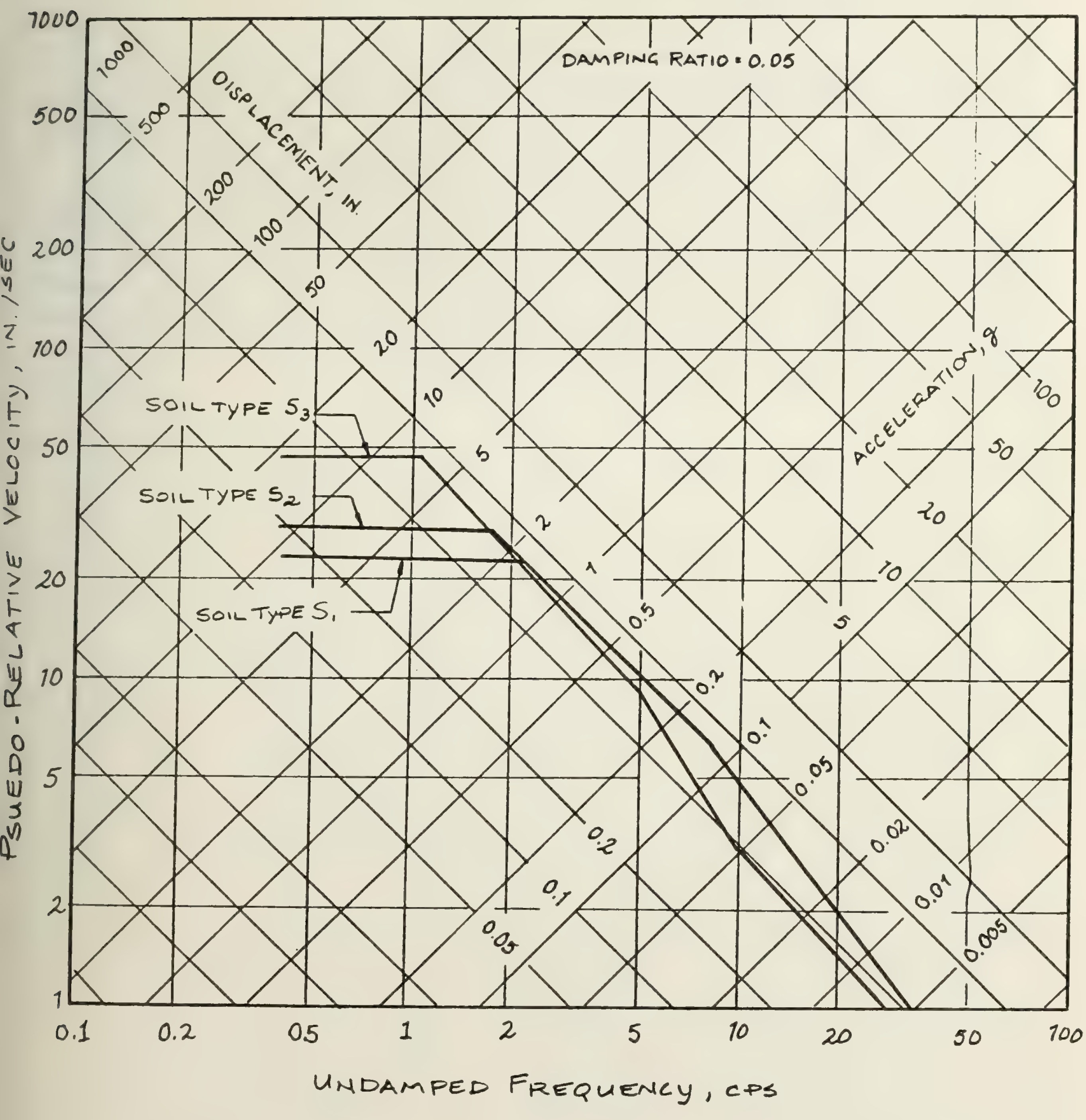


FIGURE 5-2. Ground motion spectra for Map Area 7 (A α = 0.4), (NBS, 1978).

ground motion models for peak velocity are not available. Since we are not interested in frequencies less than 0.5 Hz, it will not be necessary to estimate peak displacements.

A comparison of the three median spectral shapes for a PGA of 1g, and a damping value of 5% may be found in Fig. 5-4 for competent soil conditions and Fig. 5-5 for rock. These figures indicate that the only major disagreement among the models is for frequencies greater than 10 Hz, where the ATC shape exhibits more high-frequency content than the other two. The effect of rock is to reduce the spectral ordinates in the velocity domain for those spectra incorporating site conditions. The site-independent shape represented by the Modified Regulatory Guide 1.60 spectrum tends to fall between the soil and rock spectra of the Newmark-Hall and ATC studies. Because of the classification of stiff soil with rock in the ATC study, spectra representing both stiff soils (S_1) and deep soils (S_2) appear in Fig. 5-4. The ATC spectra are found to bracket both the site-independent Modified Reg. Guide 1.60 spectrum and the soil spectrum of Newmark-Hall.

TABLE 5-2

SPECTRUM AMPLIFICATION FACTORS FOR HORIZONTAL ELASTIC RESPONSE

(Newmark and Hall, 1982)

Damping, % Critical	One Sigma (84.1%)			Median (50%)		
	A	V	D	A	V	D
0.5	5.10	3.84	3.04	3.68	2.59	2.01
1	4.38	3.38	2.73	3.21	2.31	1.82
2	3.66	2.92	2.42	2.74	2.03	1.63
3	3.24	2.64	2.24	2.46	1.86	1.52
5	2.71	2.30	2.01	2.12	1.65	1.39
7	2.36	2.08	1.85	1.89	1.51	1.29
10	1.99	1.84	1.69	1.64	1.37	1.20
20	1.26	1.37	1.38	1.17	1.08	1.01

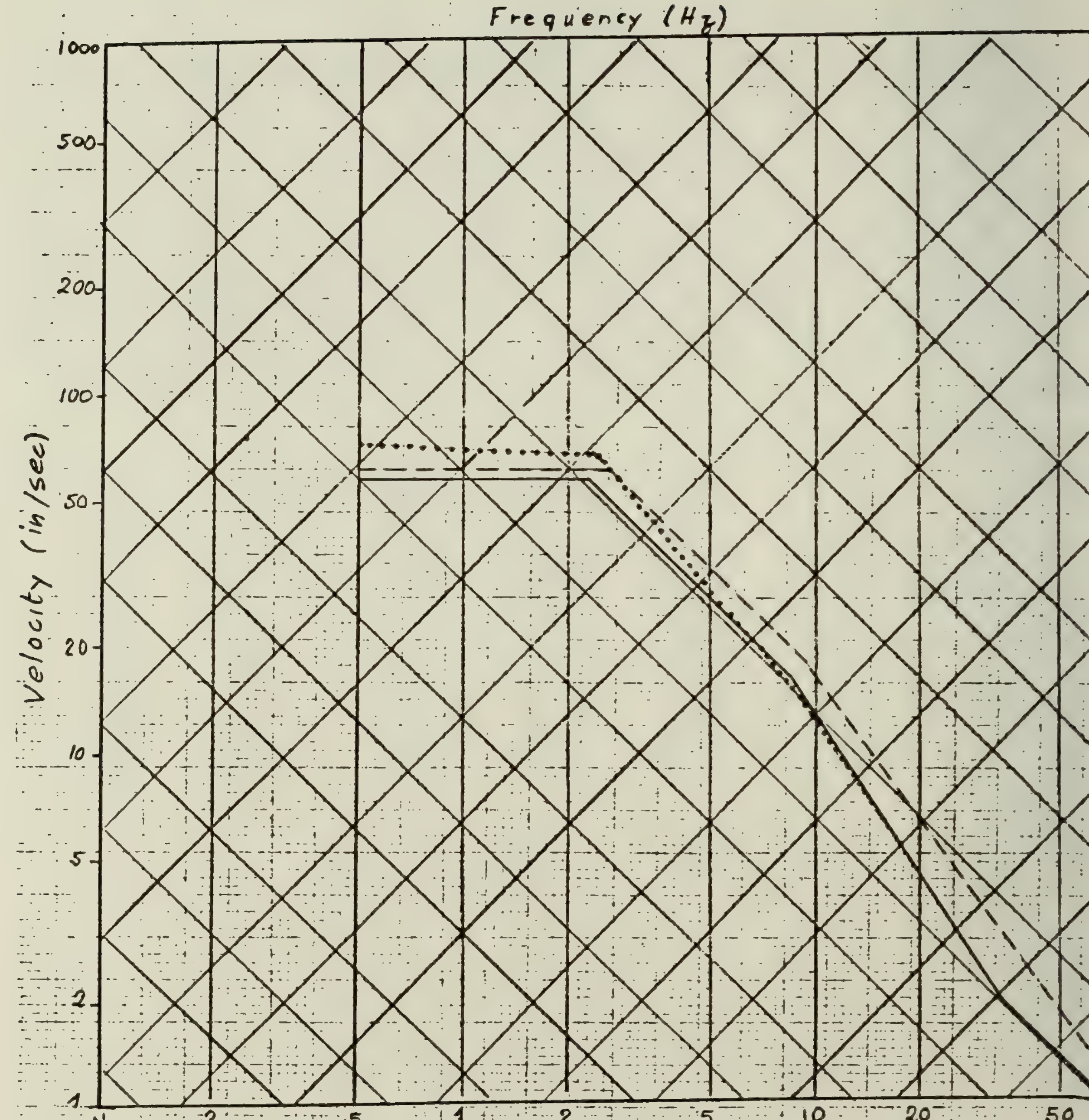


Fig. 5.5 Comparison of median spectral shape models for rock (PGA = 1
Damping = 5%)

——— Newmark-Hall
— — — ATC
· · · · · Modified Reg. Guide 1.60

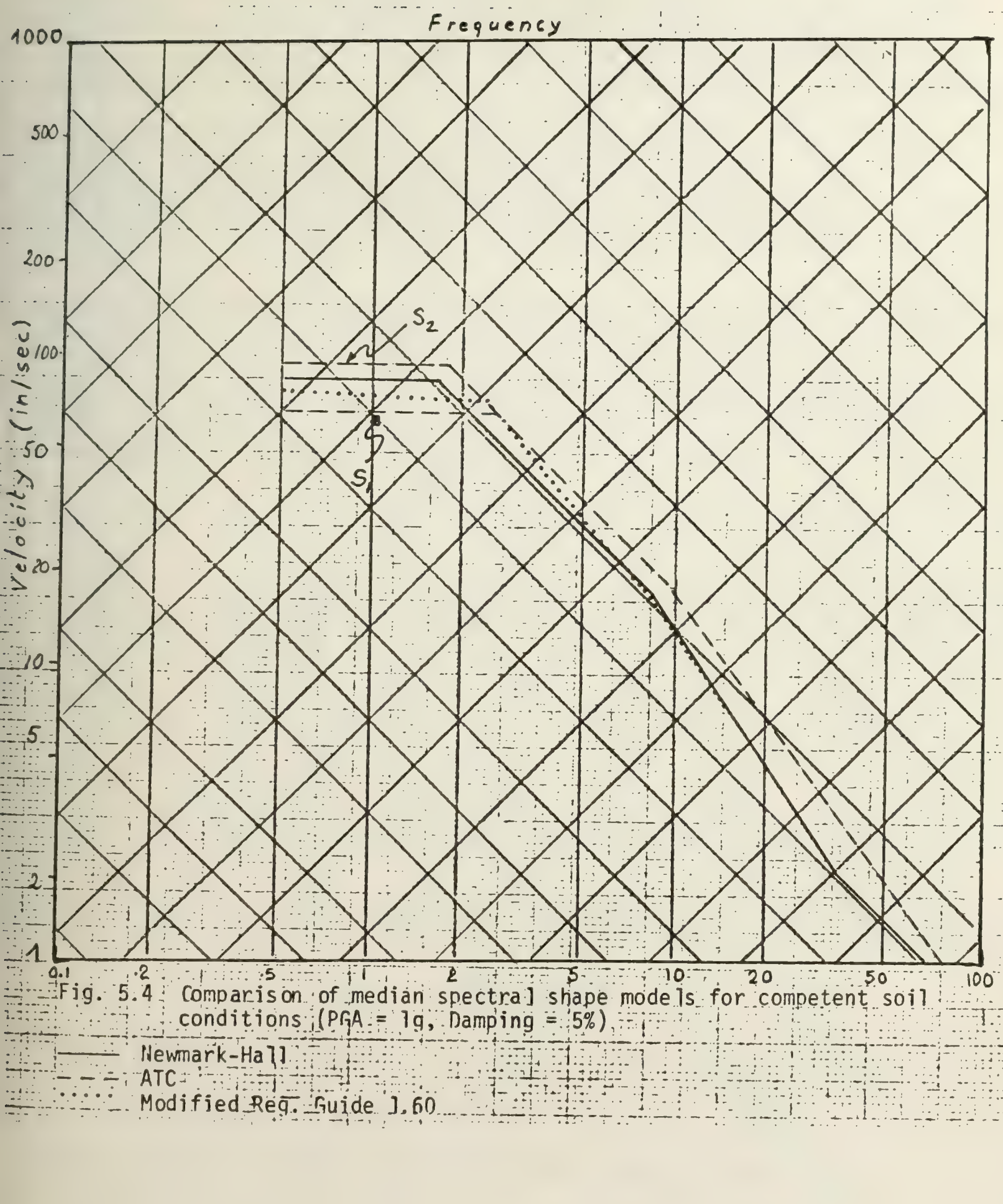


Fig. 5.4 Comparison of median spectral shape models for competent soil conditions (PGA = 1g, Damping = 5%)

——— Newmark-Hall
– – – ATC
. . . . . Modified Reg. Guide 1.60

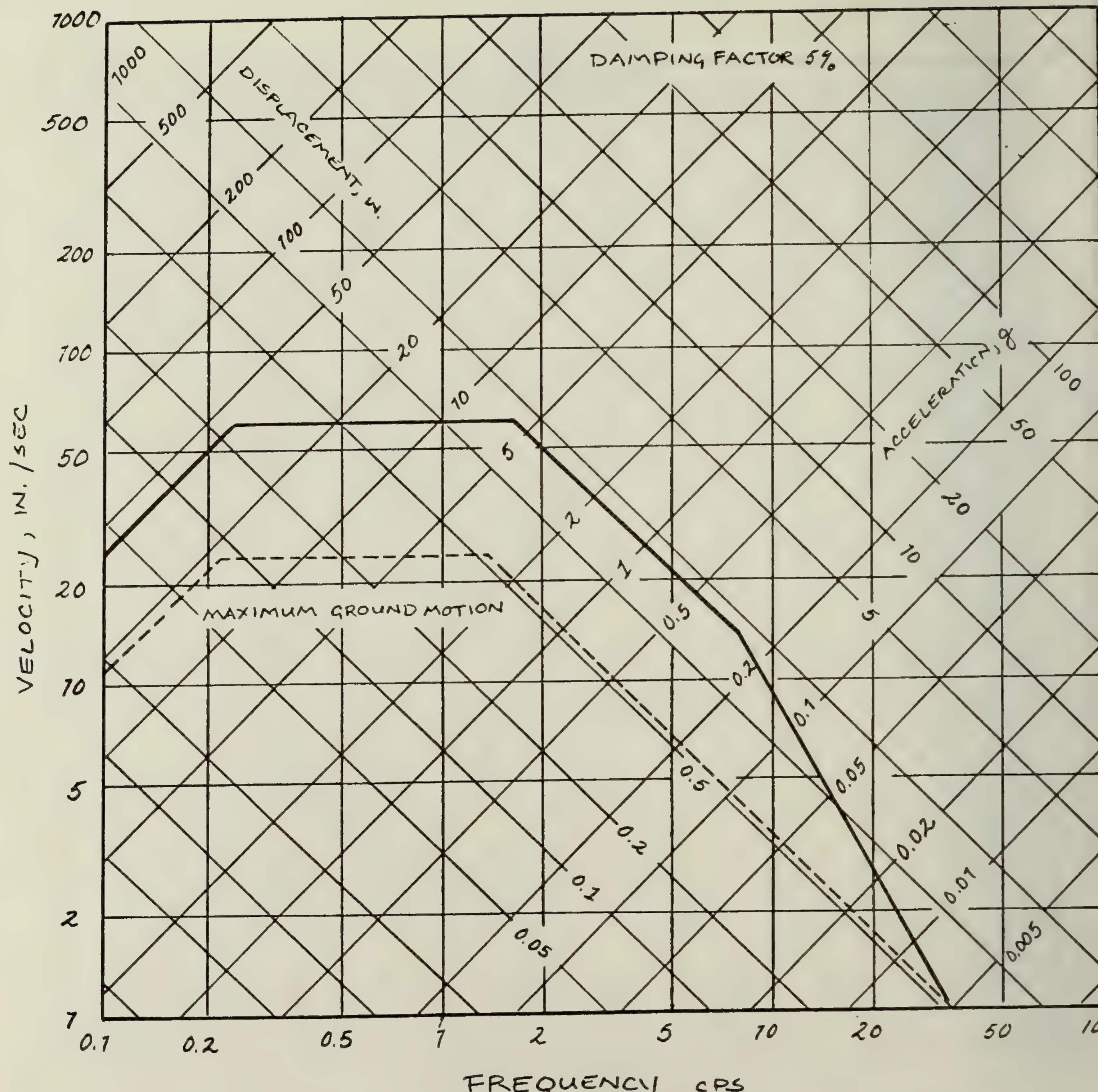


Fig. 5-3. Elastic design spectrum, horizontal motion, for 0.5 g maximum acceleration, 5% damping, one sigma cumulative probability (Newmark and Hall, 1982).

6.0. EASTERN U.S STRONG MOTION DATA

There is very little strong-motion data available in the EUS. Table 6-1 summarizes what data are currently available for earthquakes of $m_b \geq 3.0$. The recent New Brunswick aftershocks and Gaza, New Hampshire earthquake have substantially increased this data set from the three earthquakes that had been recorded prior to 1983.

In Figures 6-1 to 6-3, we compare selected maximum values of horizontal PGA, listed in Table 6-1, with the ground motion model of Nuttli App. C-A. Fig. 6-1 presents data from the New Brunswick aftershock of March 31, 1982 (m_b=4.8), Fig. 6-2 presents data from the Gaza, N.H., earthquake (m_b = 4.7), and Fig. 6-3 presents data from four New Brunswick aftershocks of m_b = 4.0-4.6.

To facilitate further comparisons, horizontal PGA data listed in Table 6-1 are plotted in groups of one-half magnitude units in Figures 6-4 to 6-7. These groups represent magnitude ranges of 3.0-3.4, 3.5-3.9, 4.0-4.4, and 4.5-5.0. These plots are drawn at the same scale as those displaying the ground motion models in Section 4. We have included clear copies of these data plots so that they may be easily overlain on any plot in Section 4 to facilitate comparison of the various ground motion models with these data.

Table 6-1

DATA FROM EUS EARTHQUAKES LARGER THAN MAGNITUDE 3.0

Date & Location	Instrument Loc.	Magnitude & Depth	Approx. Distance (km)	Comp	A_{max} (cm/s^2)	V_{max} (cm/s)	Reference & Remarks
6/13/75	New Madrid	4-4.25	9	S83W	43		Herrmann (1977)
New Madrid Area		D=9		Down	31		
				S02E	64		
3/25/76	Arkabutla	5.0	99	S28W	41		
0041 UT	Dam, Ms			Down	10		
	Toe	D=12		S62E	22		
	Crest		99	S28W	21		
				Down	6		
				S62E	10		

Table continued on next page

Table 6-1 (Continued)

DATA FROM EUS EARTHQUAKES LARGER THAN MAGNITUDE 3.0

Date & Location	Instrument Loc.	Magnitude & Depth	Approx. Distance (km)	Comp	A_{max} (cm/s^2)	V_{max} (cm/s)	Reference & Remarks
	Right abut.		99	S28W	11		
				Down	6		
				SG2E	11		
	Tiptonville TN		130	S70W	11		
				Down	12		
				S20E	17		
	New Madrid MO		131	S88W	13		
				Down	10		
				S03E	11		

Table continued on next page

Table 6-1 (Continued)

DATA FROM EUS EARTHQUAKES LARGER THAN MAGNITUDE 3.0

Date & Location	Instrument Loc.	Magnitude & Depth	Approx. Distance (km)	Comp	A_{max} (cm/s^2)	V_{max} (cm/s)	Reference & Remarks
	Wappapello Dam Mo Rt. Toe	5.0 D=12	150	S38W	10		
				Down	5		
				S52E	12		
	Right Crest		150	S38W	6		
				Down	5		
				S52E	6		
3/25/76 0100 UT	Arkabutta Dam Left Toe	4.5 D=14	99	S28W	10		
				Down	4		
				S62E	5		

Table continued on next page

Table 6-1 (Continued)

DATA FROM EUS EARTHQUAKES LARGER THAN MAGNITUDE 3.0

Date & Location	Instrument Loc.	Magnitude & Depth	Approx. Distance (km)	Comp	A_{max} (cm/s^2)	V_{max} (cm/s)	Reference & Remarks
3/31/82	Holmes	4.8	6	L	178	1.3	Weichert et al (1982)
New Brunswick	Lake			V	151	0.5	
				T	340	1.4	
	Mitchell		4	L	149	1.8	The acceleration
	Lake Rd.			V	571	2.9	values given are
				T	230	1.9	corrected values and are often significantly
	Loggie		6	L	292	1.8	higher than the raw
	Lodge			V	302	1.8	uncorrected records.
				T	564	4.1	

Table continued on next page

Table 6-1 (Continued)

DATA FROM EUS EARTHQUAKES LARGER THAN MAGNITUDE 3.0

Date & Location	Instrument Loc.	Magnitude & Depth	Approx. Distance (km)	Comp	A_{max} (cm/s^2)	V_{max} (cm/s)	Reference & Remarks
	Indian Brook		3	L	417	2.7	
				V	144	0.9	
				T	405	3.11	
	Bear Lakes		12	L	58	0.4	These are shallow earthquakes with depths of 0--4 km
				V	-	-	
				T	138	1.1	
4/2/82 New Brunswick	Mitchell Link Road	4.3	4	L	66	0.3	Late trigger Missed Most of record
				V	54	0.3	
				T	77	0.5	

Table continued on next page

Table 6-1 (Continued)

DATA FROM EUS EARTHQUAKES LARGER THAN MAGNITUDE 3.0

Date & Location	Instrument Loc.	Magnitude & Depth	Approx. Distance (km)	Comp	A_{max} (cm/s^2)	V_{max} (cm/s)	Reference & Remarks
	Bear Lakes		12	L	-	-	
				V	-	-	
				T	44	0.4	
4/11/82	Bear Lakes	4.1	12	T	77	0.5	Late Trigger
4/28/82	Holmes Lake	3.4	6	L	74	0.3	Late Trigger
				V	41	0.2	
				T	56	0.3	

Table continued on next page

Table 6-1 (Continued)

DATA FROM EUS EARTHQUAKES LARGER THAN MAGNITUDE 3.0

Date & Location	Instrument Loc.	Magnitude & Depth	Approx. Distance (km)	Comp	A_{max} (cm/s^2)	V_{max} (cm/s)	Reference & Remarks
5/6/82	Holms	4.0	6	L	42	0.3	Weichert et al. (1982)
New Brunswick	Lake			V	24	0.2	
				T	71	0.7	Late Trigger
	Mitchell		4	L	54	0.4	
	Lk. Rd.			T	176	0.6	
				V	33	0.2	
	Loggie		7	L	115	1.4	
	Lodge			V	66	0.7	
				T	146	1.8	

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Table 6-1 (Continued)

DATA FROM EUS EARTHQUAKES LARGER THAN MAGNITUDE 3.0

Date & Location	Instrument Loc.	Magnitude & Depth	Approx. Distance (km)	Comp	A_{max} (cm/s^2)	V_{max} (cm/s)	Reference & Remarks
7/28/82	Indian Brook	3.7	1	L	300		
				V	180		
				T	230		
6/16/82 New Brunswick	Mitchell Lake Rd.	4.6	25	L	48	0.3	
				V	26	0.2	
				T	10	0.08	
	Indian Brook		27	L	15	0.2	
				V	27	0.2	
				T	17	0.1	

Table continued on next page

Table 6-1 (Continued)

DATA FROM EUS EARTHQUAKES LARGER THAN MAGNITUDE 3.0

Date & Location	Instrument Loc.	Magnitude & Depth	Approx. Distance (km)	Comp	A_{max} (cm/s^2)	V_{max} (cm/s)	Reference & Remarks
New Brunswick 1/17/82 13:33:56.2GMT	7A	3.5 D=3.5	8	V	83	0.4	Cranswick et. al (1982) A number of recordings were made for small earthquakes. Only the largest for which an estimate of the magnitude is available, is listed
				H1	83	1.2	
				H2	60	0.9	
	8A		10	V	18	0.1	
				H1	18	0.2	
				H2	14	0.2	
1/19/82 Gaza, NH	Franklin Falls Dam Abut.	4.7 D=5	8	L	288		Toksoz (1982) and digitized records obtained from the NRC
				V	173		
				T	540		
	Franklin Falls Dam Downstream		8	L	141		
				V	271		
				T	378		

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Table 6-1 (Continued)

DATA FROM EUS EARTHQUAKES LARGER THAN MAGNITUDE 3.0

Date & Location	Instrument Loc.	Magnitude & Depth	Approx. Distance (km)	Comp	A_{max} (cm/s^2)	V_{max} (cm/s)	Reference & Remarks
	Franklin Falls Dam Crest		8	L	124		
				V	114		
				T	307		
	Union Village Dam Down-stream		60	L	37		
				V	29		
				T	23		
	Abutment		60	L	9		
				V	6		
				T	8		
	Crest		60	L	22		
				V	23		
				T	25		

Table continued on next page

Table 6-1 (Continued)

DATA FROM EUS EARTHQUAKES LARGER THAN MAGNITUDE 3.0

Date & Location	Instrument Loc.	Magnitude & Depth	Approx. Distance (km)	Comp	A_{max} (cm/s^2)	V_{max} (cm/s)	Reference & Remarks
	North Hart Dam Abut.		61	L	11		
				V	4		
				T	7		
	Crest		61	L	37		
				V	16		
				T	38		
	N. Spring-field Dam Downstream		76	L	31		
				V	14		
				T	23		
	Crest		76	L	24		
				V	22		
				T	22		

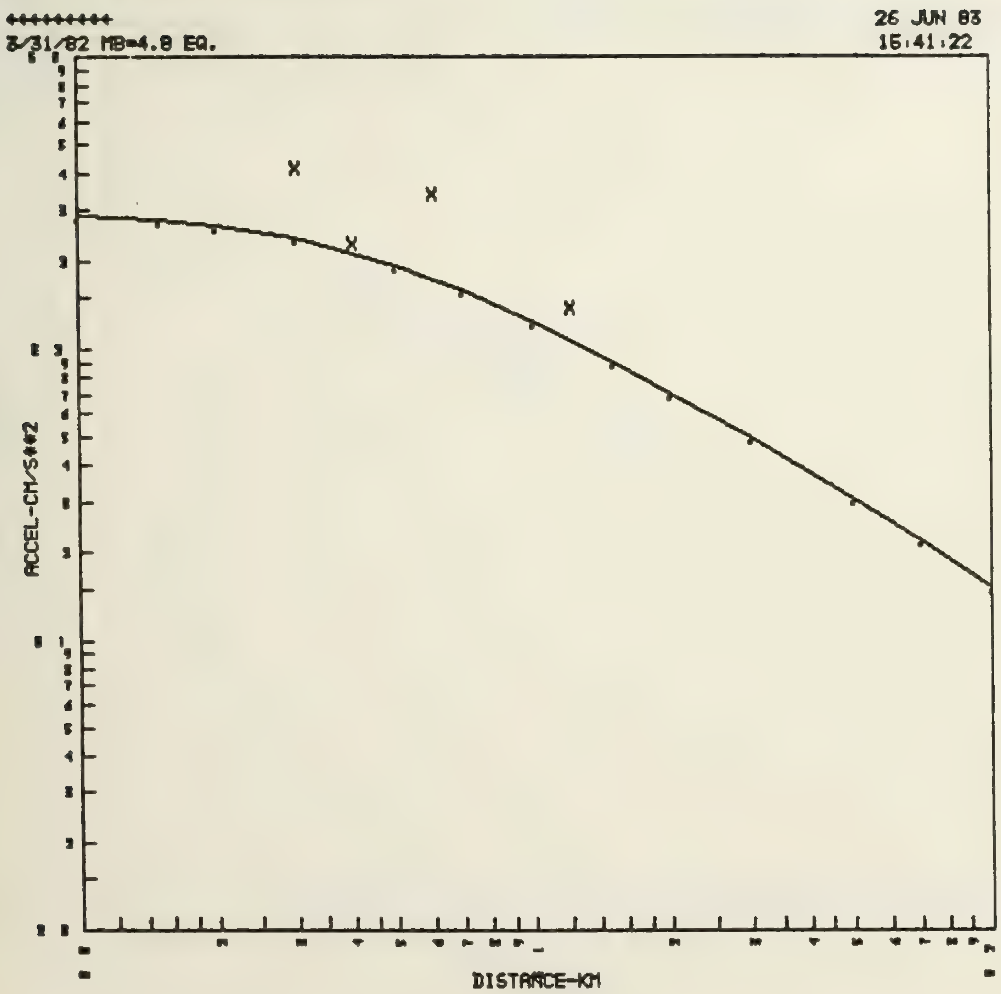

Figure 6-1 Nuttli's (App. C-A) model compared to data from the New Brunswick aftershock of 3/31/82 (m_b = 4.8).

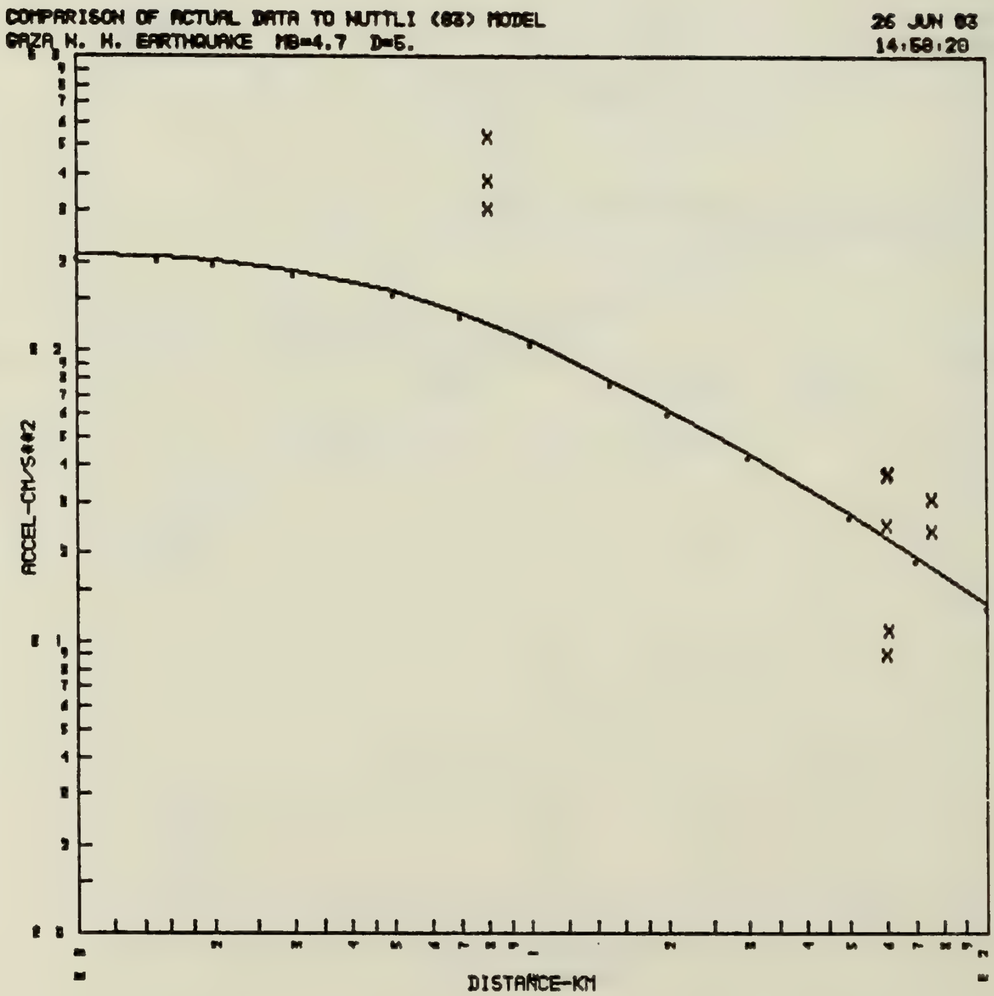

Figure 6-2 Nuttli's (App. C-A) model compared to data from the Gaza, N.H., earthquake (m_b = 4.7).

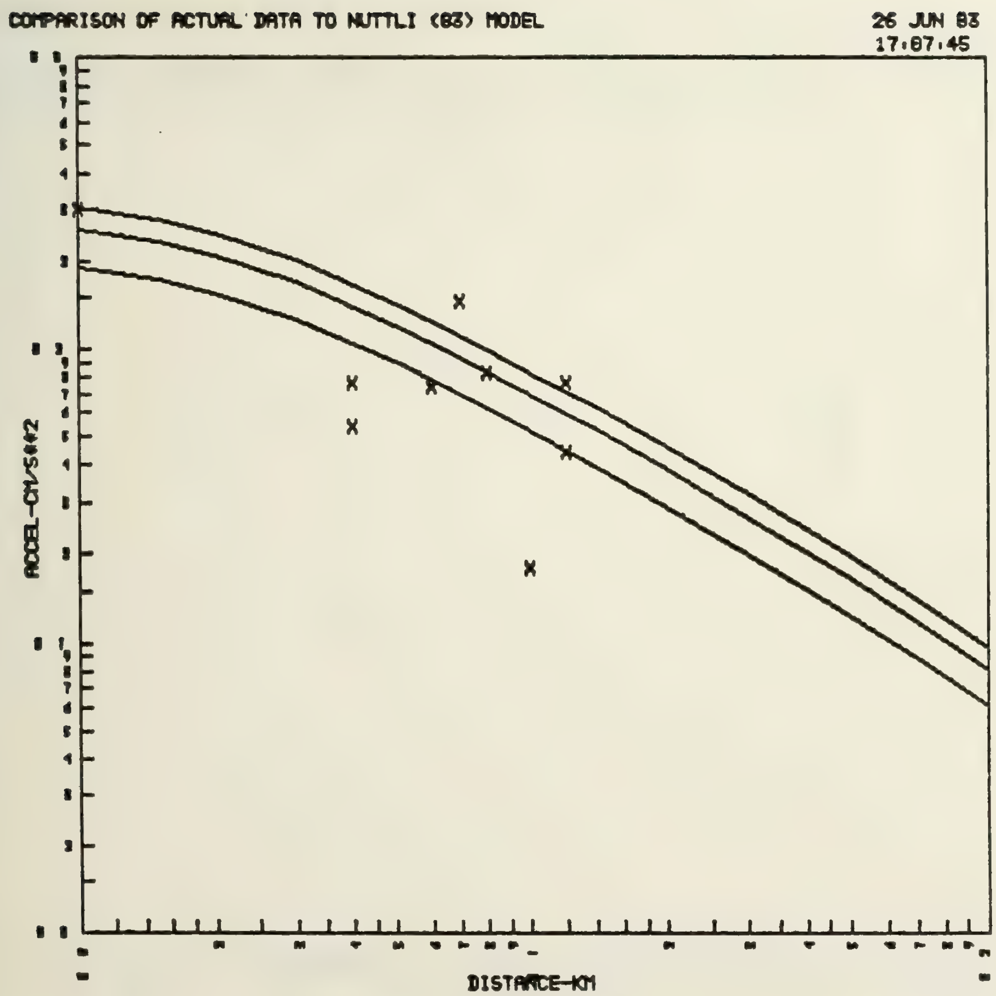

Figure 6-3 Data from New Brunswick aftershocks (m_b = 4.0 - 4.6) compared to Nuttli's (App. C-A) model for m_b = 3.5, 4.0, 4.3 D=2km.

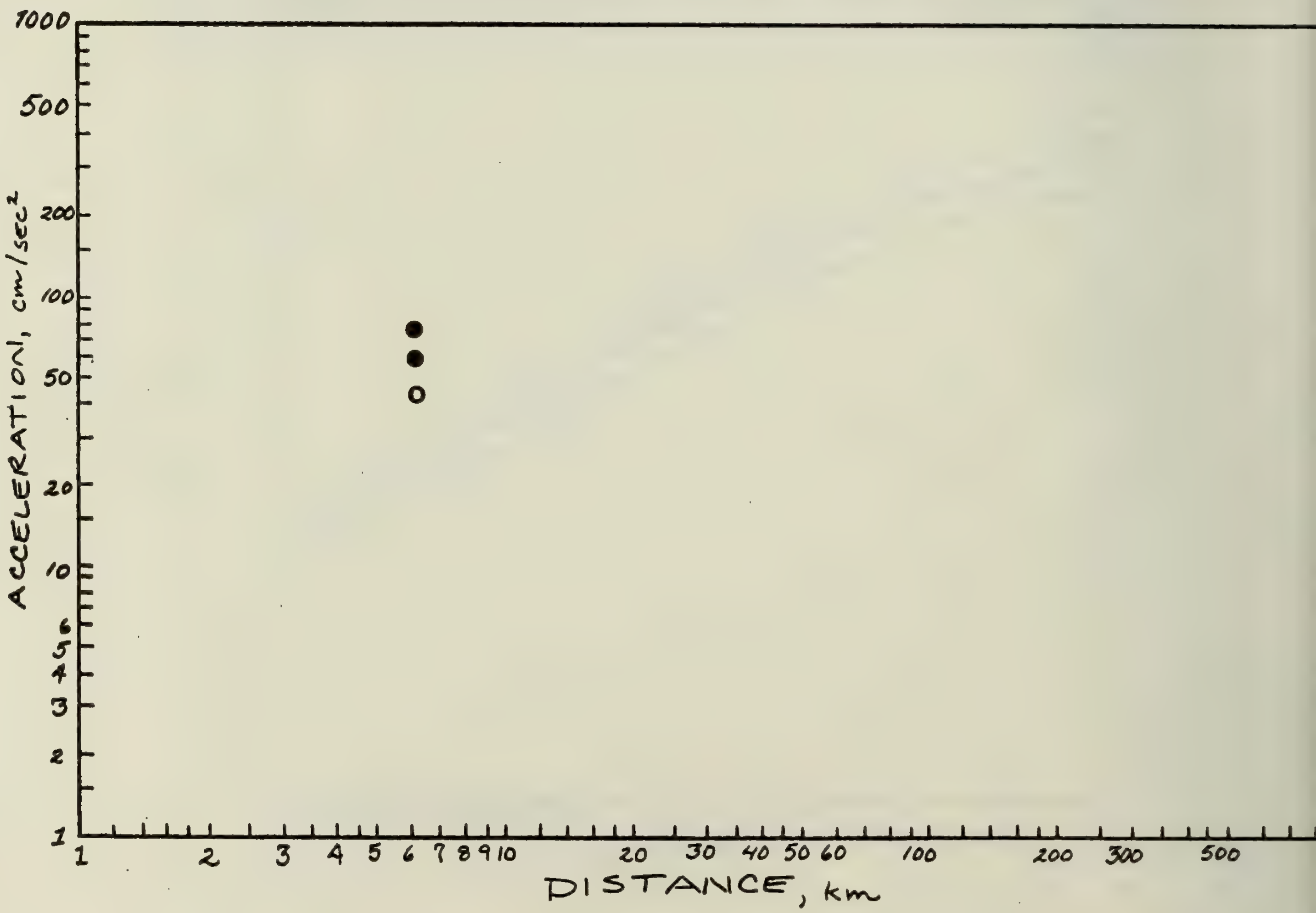

Figure 6.4 EUS strong motion data from earthquakes of m_b = 3.0 - 3.4.

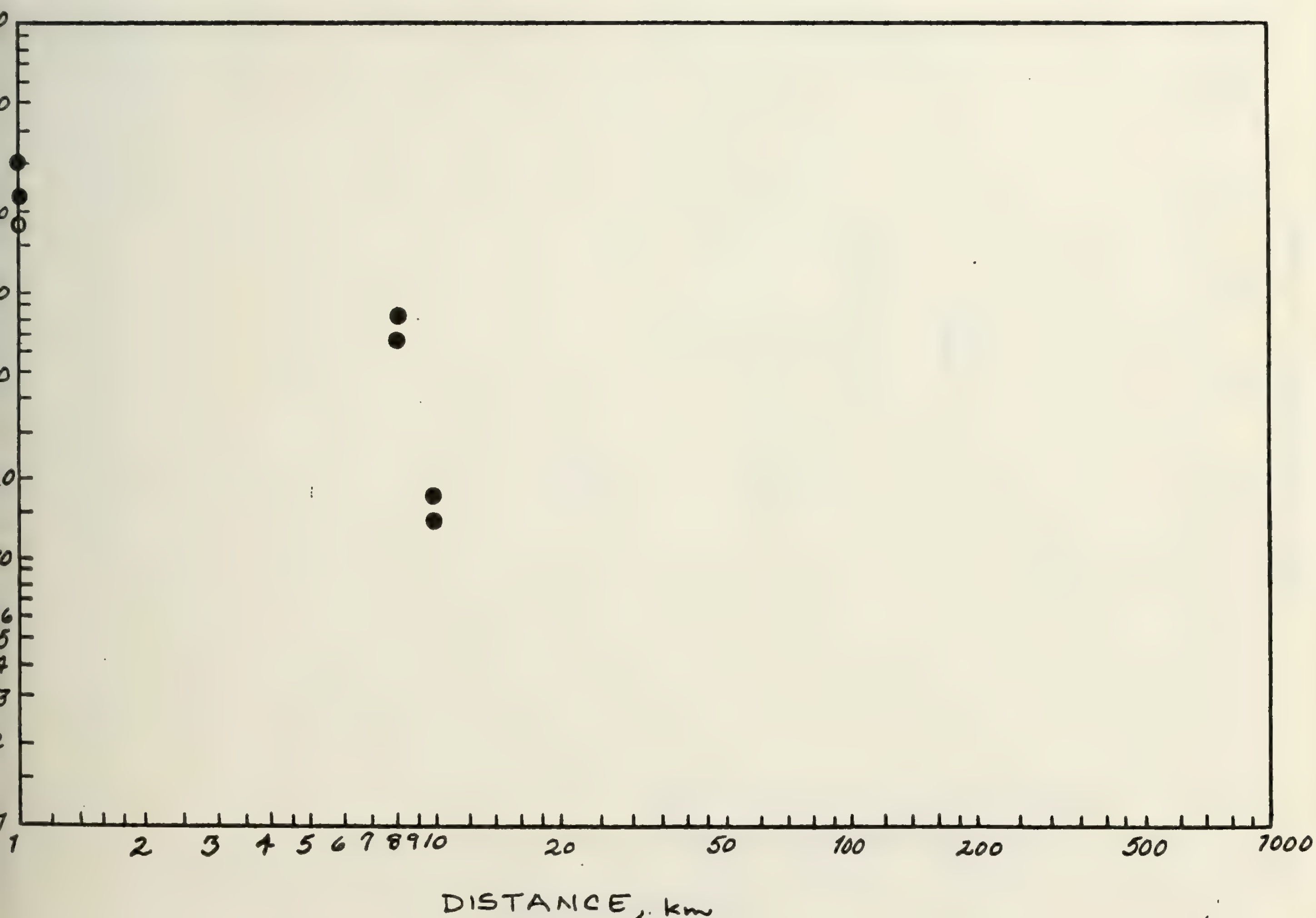

Figure 6.5 EUS strong motion data from earthquakes of m_b = 3.5 - 3.9.

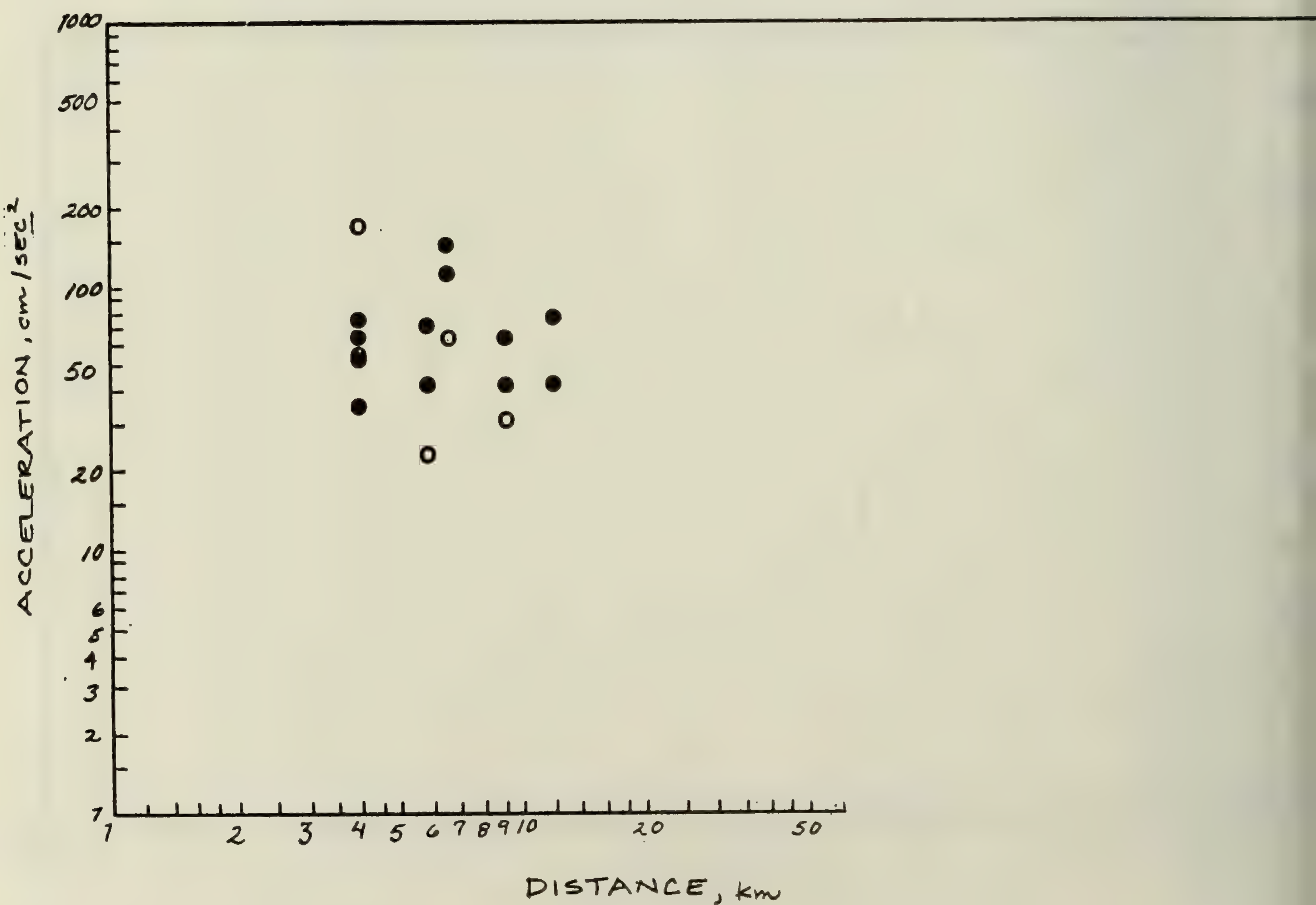

Figure 6.6 EUS strong motion data from earthquakes of m_b = 4.0 - 4.4.

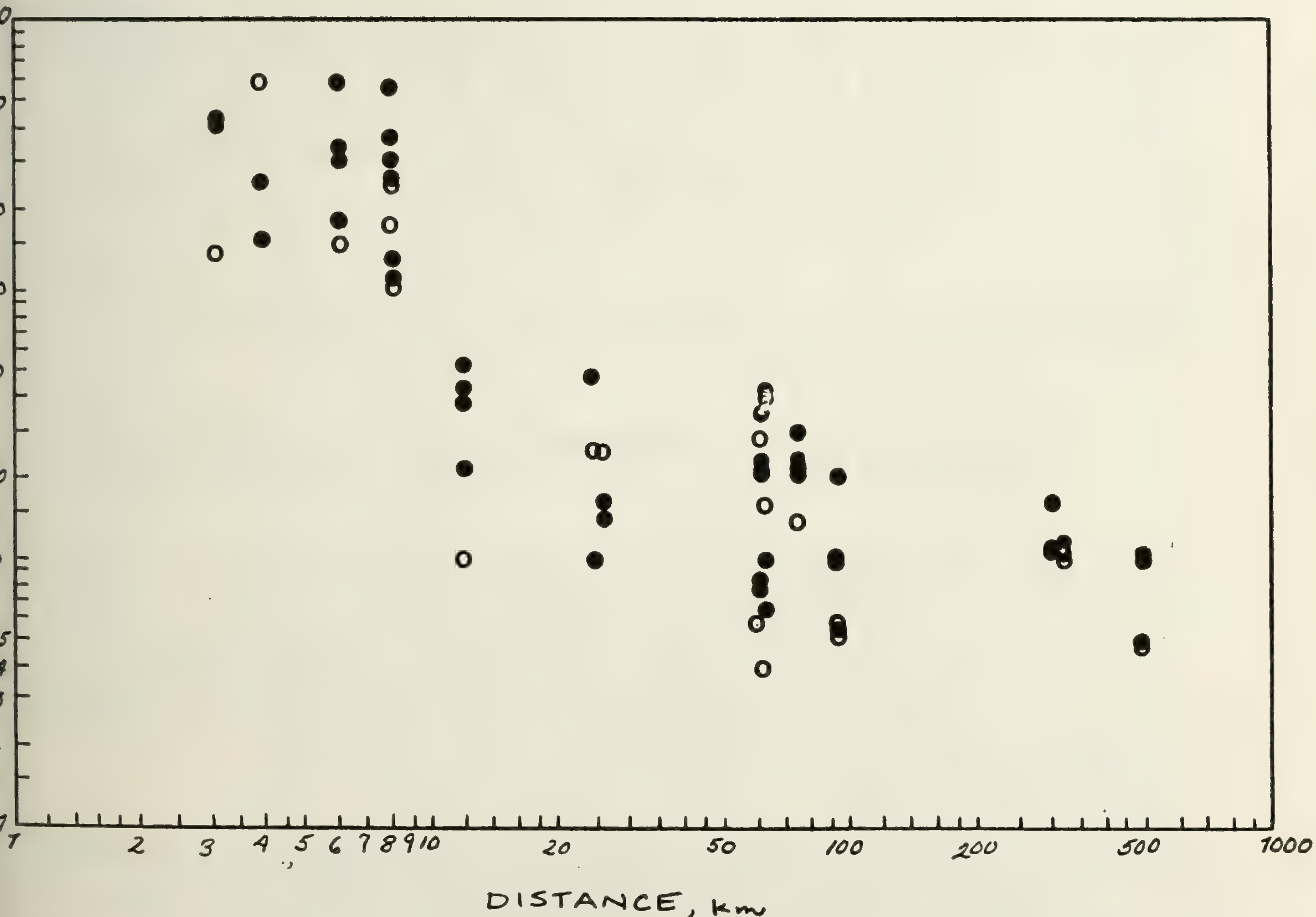

Figure 6.7 EUS strong motion data from earthquakes of m_b = 4.5 - 5.0.

7.0 QUESTIONNAIRE

7.1 INTRODUCTION

As part of the seismic hazard characterization of the Eastern United States, it is necessary to select an appropriate set of ground motion models to be used in assessing the seismic hazard at a specified site. This questionnaire is designed to elicit your opinion about the selection of the most appropriate models.

The previous sections contain a general discussion, based primarily on PGA, of EUS ground motion models which we would like you to consider in making your recommendations for the most appropriate models. We also will ask you to provide additional models if you feel they are needed. The collection of models chosen for your consideration were based on the discussion during the meeting of the panel, January 11-13, 1983, our review of the literature, and our judgment of the validity of the models to describe the attenuation of seismic energy and the ground motion at locations throughout the EUS.

As discussed in the previous sections, we have found it appropriate to partition the available ground motion models into two major categories:

1. Intensity Based Models

   Models based on using intensity as an intermediary variable to model ground motion as a function of the earthquake parameters. Most such models involve a combination of

   - an intensity-attenuation relation, $I_s = F(I_o,R)$, which relates site intensity to source intensity, and

   - a ground motion parameter-site intensity relation, GMP = $G(I_s,M,R)$ which relates ground motion parameters to site intensity and, perhaps, other earthquake characteristics such as magnitude and distance.

2. Direct Models

   Models based on using available data to model directly the ground motion parameter in terms of the earthquake parameters such as magnitude and source-to-site distance. Such models are generally based on the "theoretical attenuation curve"

   $$GMP = K(M)R^{-a} \exp(-\gamma R)$$

   where γ is the absorption coefficient and K(M) is a scale factor which is often expressed as a function of magnitude.

The former category, the Intensity Based Models, have been subdivided into five subcategories:

1-1. No Weighting: model combinations

$$I_s = F(I_o,R)$$
$$GMP = G(I_s)$$

in which the ground motion parameter is related to site intensity only.

1-2. Distance Weighting: model combinations

$$I_s = F(I_o,R)$$
$$GMP = G(I_s,R)$$

in which the ground motion parameter is related to site intensity and source-to-site distance.

1-3. Magnitude Weighting: model combinations

$$I_s = F(I_o,R)$$
$$GMP = G(I_s,M)$$

in which the ground motion parameter is related to site intensity and source magnitude.

1-4. Magnitude and Distance Weighting: model combinations

$$I_s = F(I_o,R)$$
$$GMP = G(I_s,M,R)$$

in which the ground motion parameter is related to site intensity, source magnitude, and source-to-site distance.

1-5. Semi-Empirical: models

$$GMP = H(M,R)$$

relating the ground motion parameter to earthquake magnitude and distance, but based on using intensity as an intermediary variable.

Note that subgroups 1-1 through 1-4 involve a pair of models which, in our hazard analysis, will be combined to relate the ground motion parameter to the earthquake parameters M and R. Since the intensity-attenuation model is derived independently of the ground motion parameter-site intensity model, any one of a number of intensity models can be combined with any of the ground motion parameter models.

The latter category group, the Direct Models, have been subdivided into two subcategories, based on the parameters which are expected to vary between the WUS and the EUS:

- models in which only the absorption coefficient γ (or the quality factor Q) is assumed to be different for WUS and EUS;

- models in which both the absorption coefficient γ and the scale parameter K(M) varies between the WUS and EUS.

Considering all possible combinations, we have identified 59 models for the peak ground acceleration PGA. Ideally, for each of these there would be a corresponding model for PGV and a corresponding set of spectra models. Unfortunately, not all PGA models have a corresponding model for PGV and there are only a few spectra models. Ideally, the same type of model would be used for all 3 parameters in the hazard analysis. However, to give you as much flexibility as possible in choosing the most appropriate models we will ask you to rank the models separately for PGA, PGV and spectra.

In characterizing the seismicity within a zone, the earthquake size is expressed in either magnitude or epicentral intensity. To estimate the hazard at a site it is necessary to assess the hazard based on each of the ground motion models. Since some ground motion models are expressed in terms of epicentral intensity and others in magnitude, a conversion of magnitude scales is required at some level. After consideration of the alternatives, we have chosen to make this conversion at the ground motion level. Thus, it is necessary to express each ground motion model in terms of both epicentral intensity and magnitude. To accomplish this conversion, we asked each member of our EUS Seismicity Panel to provide the proper conversions between scales. Since you may not feel that a ground motion model expressed in epicentral intensity to be as appropriate when converted to a model involving magnitude or vice versa, we will be asking you to select a separate set of models for intensity and magnitude.

Another issue which must be addressed in the selection of ground motion models is the question of the distance measure. Our hazard analysis is based on treating earthquakes as point sources so that the distance R in the ground motion model is treated as an epicentral distance. It must be recognized that some of the ground motion models are based on fault distance rather than epicentral distance. Thus, our treatment of R as epicentral distance may influence your choice of appropriate models. See Section 1.0 for additional discussion on this issue.

Finally, as discussed in Section 2.4, the choice of the ground motion model has a direct influence on the outcome of the hazard analysis. This influence is a function of the model as well as the extent of the random variation in the ground motion parameter (GMP). For purposes of the hazard analysis, we are approximating the random variation in the ground motion parameter by a lognormal distribution for which the ground motion model describes the expected value of the logarithm of GMP, given the earthquake parameters. Random variation is the inherent variation in GMP about its expected value due to a lot of unidentifiable factors. The extent of the random variation in GMP is described by the standard deviation of the logarithm of GMP (which is approximately the coefficient of variation of GMP). We will be asking you to estimate this standard deviation. In making an estimate it is important to

recognize that the standard deviation associated with a specific ground motion model usually has both a random variation component as well as a modeling uncertainty component (see Section 2.4 of the accompanying report). It is the random component of this uncertainty that is of interest in this study. The modeling uncertainty is accounted for in the use of several models.

7.2 SELECTION PROCESS

We have identified four regions in the EUS, shown in Fig.7.1, for which it may be appropriate to change the values of some of the model coefficients, e.g., γ in the direct models. Also, a particular ground motion model may be appropriate for one region but not applicable in another. Thus, we will be asking you to select appropriate models for each of the four regions. We recognize that the actual physical situation is much more complex and the boundaries cannot be simply drawn, however, at this stage of the analysis we will limit the complexity of our model by partitioning the EUS into the four identified regions.

We have limited our analysis to the use of two "magnitude" scales, intensity (MMI) and body wave magnitude (m_b). It should be noted that (as discussed in Section 3.4) we are assuming m_{bLg} and m_b to be essentially equivalent. For simplicity we use the term m_b even though most of the magnitudes in the catalogs are in fact m_{bLg}.

Weighing the merits of using all the models available to describe ground motion versus (1) our capability to handle a large number of models in the hazard analysis and (2) your ability to reasonably distinguish between the models so as to rate them for their appropriateness has led us to the following method for eliciting your opinion about the ground motion models.

We have divided the ground motion models into seven subcategories identified in Section 7.1, five subgroups of Intensity Based Models and two subgroups of Direct Models. The models in each subcategory are catalogued in Section 7.3. For each of the two magnitude scales in each of the four regions (a total of 8 combinations) we would like you to:

For peak ground acceleration and peak ground velocity,

- o Select from among <u>all</u> the models the <u>one</u> model which you consider the <u>most appropriate</u>. This is labeled the <u>Best Estimate Model</u>. (Note: if this model is an Intensity Based Ground Motion Model, the Best Estimate would consist of 2 models, an attenuation model and a GMP model.)

- o For each of the seven (7) classes of models identified above, select the most appropriate model within the subcategory. Assign a <u>relative</u> "level of confidence" to each of the models. (Note: the sum of the confidences over the seven subcategories should equal 1.0.)

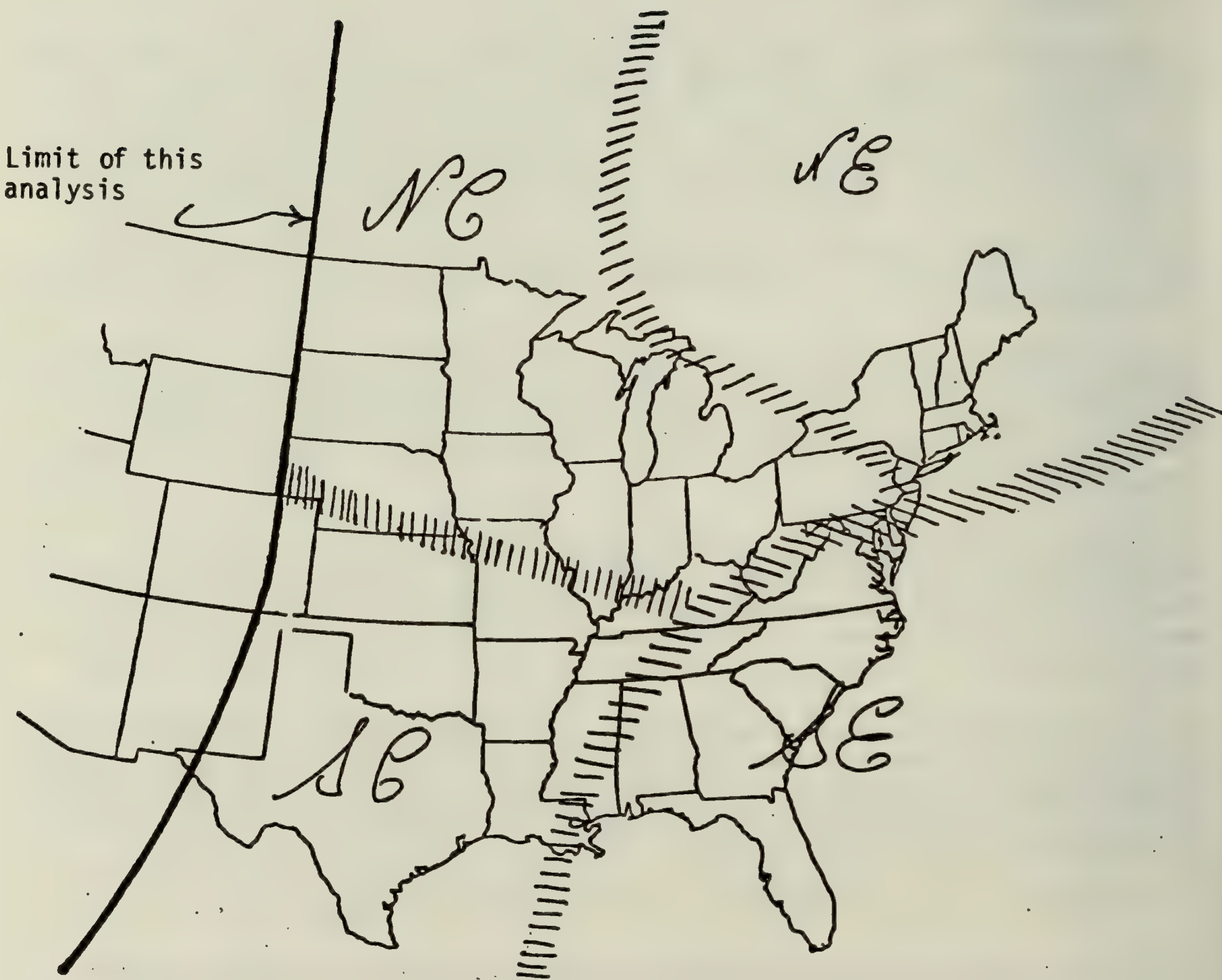

Fig. 7.1 Identification of four regions of the Eastern U.S. based on a compilation of the seismic zonation expert maps developed in this study, combined with a map of Q_0-contours from Singh & Herrmann (1983).

The "level of confidence" we ask you to express for each model is considered to reflect your degree of belief that the data, the modeling process, your knowledge of seismic attenuation and ground motion and any other relevant information supports the use of the specific model to describe ground motion within the given region. We expect that your "level of confidence" will reflect, to some degree, your opinions about the use of each of the different types of models (based on different modeling philosophies) for modeling ground motion. At a later date we will ask you to provide weights for all of the models (including any that different panel members may suggest).

For the spectra models,

- o Select the set (one for each frequency) of models which you consider most appropriate.

- o Assign a relative "level of confidence" to each of the models (Note: a zero level of confidence is acceptable).

7.3 MODELS

7.3.1 Peak Ground Acceleration

I. Intensity Based Models

Except for the models in Subcategory I-5, a ground motion model is a combination of (a) an intensity-attenuation model and (b) a ground motion parameter-site intensity model. The latter models form the basis of the Subcategories I-1 through I-4. The former models are:

A1. Bollinger (Charleston, South Carolina earthquake)

$$I_s = 2.87 + I_o - 0.00052R - 1.25 \ln R \quad , R \geq 10$$

$$I_s = I_o \quad , R < 10$$

A2. Bollinger (Giles County, Virginia earthquake)

$$I_s = 0.35 + I_o - 0.0038R - 0.34 \ln R$$

A3. Modified Gupta-Nuttli (Central U.S.)

$$I_s = 3.2 + I_o - 0.0011R - 1.17 \ln R \quad , R \geq 15$$

$$I_s = I_o \quad , R < 15$$

A4. LLNL (Southern Illinois earthquake)

$$I_s = 0.35 + I_o - 0.0046R - 0.31 \ln R$$

A5. Weston Geophysical Corporation (Ossippee earthquake)

$$I_s = 0.441 + I_o - 0.004R - 0.67 \ln R$$

Subcategory I-1. No Weighting (Equation number from Section 4)

G11. LLNL (1983) (Eq. 4-8)

$$\ln(a) = -1.69 + 0.86\, I_s$$

G12. LLNL (1983) (Eq. 4-9)

$$\ln(a) = -2.32 + 0.96\, I_s$$

G13. McGuire (1977) (Eqs. 4-3 and 4-7)

$$\ln(a) = \begin{cases} -0.83 + 0.85\, I_s & \text{(medium sites)} \\ 0.27 + 0.6\, I_s & \text{(soft sites)} \end{cases}$$

G14. Trifunac and Brady (1975) (Eq. 4-5)

$$\ln(a) = 0.032 + 0.69\, I_s$$

G15. Murphy and O'Brien (1977) (Eq. 4-6)

$$\ln(a) = 0.58 + 0.58\, I_s$$

G16. Trifunac (1976) (Eq. 4-4)

$$\ln(a) = -0.19 + 0.67\, I_s + 0.33S$$

S = 0 (alluvium)
S = 1 (intermediate rock sites)
S = 2 (basement rock sites)

Subcategory I-2. Distance Weighting

G21. Bernreuter (1981a) (Eq. 4-13)

$$\ln(a) = 1.79 + 0.57\, I_s - 0.323 \ln R$$

G22. McGuire (1977) (Eqs. 4-11 and 4-12)

$$\ln(a) = \begin{cases} 1.45 + 0.68\, I_s - 0.359 \ln R & \text{(medium sites)} \\ 2.01 + 0.51\, I_s - 0.313 \ln R & \text{(soft sites)} \end{cases}$$

Subcategory I-3. Magnitude Weighting

G31. Bernreuter (1981a) (Eq. 4-15)

$$\ln(a) = 0.96 + 0.63\, I_s - 0.13\, M_L$$

Subcategory I-4. Magnitude and Distance Weighting

G41. Murphy and O'Brien (1978) (Eq. 4-16)

$$\ln(a) = 1.38 + 0.32\, I_s + 0.55\, M_L - 0.68 \ln R$$

Subcategory I-5. Semi-Empirical

G51. Battis (1981) (Eq. 4-29)

$$\ln(a) = 3.16 + 1.24\, m_b - 1.24 \ln (R + 25)$$

G52. Nuttli and Herrmann (1978) (Eq. 4-23)

$$\ln(a) = 1.47 + 1.2\, m_{bLg} - 1.02 \ln R; \; R > 15 \text{ km}$$

G53. Weston Geophysical Corp. (Eq. 4-31)

$$\ln(a) = 1.47 + 1.1\, m_b - 0.0017R - 0.88 \ln R$$

II. Direct Models

Subcategory II-1. γ Variable

D11. Campbell (1981b) (Eq. 4-41)

$$\ln(a) = 2.64 + 0.79M - (0.023 - 0.0048M + 0.00028\, M^2)R - 0.862 \ln [R + 0.0286 \exp(0.778M)]$$

where R = closest distance to fault rupture

D12. Campbell (1981b) (Eq. 4-42)

$$\ln(a) = 4.39 + 0.922M - 0.023R + 0.0048RM - 0.00028RM^2 - 1.27 \ln (R + 25.7)$$

where R is epicentral distance, and for both D11 and D12

$$M = \begin{cases} 1.02\, m_b + 0.30 & (m_b < 5.59) \\ 1.64\, m_b - 3.16 & (m_b \geq 5.59) \end{cases}$$

D13. Campbell (1982) (Eq. 4-48)

$$\ln(a) = -4.29 + 0.777M - 0.797 \ln[R + 0.012 \exp(0.898M)] - \gamma R$$

where R = closest distance to fault rupture and
γ = frequency-dependent absorption coefficient (e.g. Singh and Herrmann, 1983)

D14. Nuttli (1979) (Eq. 4-34)

$$\ln l(a) = 1.481 + 1.15\, m_b - (0.0136 - 0.00172\, m_b)R - 0.833 \ln R$$

D15. SSMRP (Eq. 4-37)

$$\ln(a) = 3.99 + 0.59\, m_b - 0.003\, (R^2 + 28.09)^{1/2} - 0.833 \ln (R^2 + 28.09)^{1/2}$$

where R = closest distance to surface projection of fault rupture.

Subcategory II-2. γ and m_b Variable

D21. Nuttli (App. C-A)

$$\ln(a) = \begin{cases} 3.892 + 0.576\, m_b - 0.834 \ln [R^2 + \exp(-4.371 + 1.308\, m_b)]^{1/2} - 0.00281\, (R-1) & m_b \leq 4.4 \\ 1.313 + 1.15\, m_b - 0.833 \ln [R^2 + \exp(-7.968 + 2.100\, m_b)]^{1/2} - 0.00281\, (R-1) & 4.4 < m_b \leq 7.4 \end{cases}$$

7.3.2 Peak Ground Velocity

I. Intensity-attenuation models, A1 through A5 are the same as in Section 7.3.1.

Subcategory I-1. No Weighting

GV11. McGuire (1977)

$$\ln(v) = \begin{cases} -4.02 + 0.952\, I_s & \text{(medium sites)} \\ -1.51 + 0.543\, I_s & \text{(soft sites)} \end{cases}$$

GV12. Trifunac (1976)

$$\ln(v) = -2.25 + 0.67\, I_s + 0.032\, S$$

S = 0 (alluvium)

S = 1 (intermediate rock sites)

S = 2 (basement rock sites)

GV13. Trifunac and Brady (1975)

$$\ln(v) = -1.45 + 0.58\, I_s$$

Subcategory I-2. Distance Weighting

GV21. Bernreuter (1981a)

$$\ln(v) = -2.94 + 0.76\, I_s + 0.06 \ln R$$

GV22. McGuire (1977)

$$\ln(v) = \begin{cases} -3.61 + 0.923\, I_s - 0.064 \ln R & \text{(medium sites)} \\ -1.11 + 0.521\, I_s - 0.072 \ln R & \text{(soft sites)} \end{cases}$$

Subcategory I-3. Magnitude Weighting

GV31. Bernreuter (1981a)

$$\ln(v) = -2.62 + 0.51\, I_s + 0.17\, M_L$$

Subcategory I-4. Magnitude and Distance Weighting
(No models)

Subcategory I-5. Semi-Empirical

GV51. Nuttli - Herrmann (1978)
$\ln(v) = -6.72 + 2.3\ m_b - \ln R$

GV52. Western Geophysical Corporation

$$\ln(v) = -0.924 + .95\ m_b - .0023R - .765 \ln R$$
$$+ .923E_1 + E_2$$

where E_1 and E_2 are random variables with mean zero and standard deviation σ_1 and σ_2. E_1 and E_2 represent the error terms in the fit of site intensity versus source intensity and distance, and the fit of site intensity as a function of magnitude and distance, respectively.

II. Direct Models

Subcategory II-1.

DV11. Nuttli (1979)
This model only appears in the form of a set of curves of velocity versus distance and magnitude. The reader is referred to the publication (Nuttli, 1979).

DV12. SSMRP(a)
$\ln(v) = -7.86 + 2.3\ m_b - C_vR - .835 \ln R$
where $C_v = .0076 - .00099\ m_b$

DV13. SSMRP(b)
$\ln(v) = -\ .963 + 1.15\ m_b - C_vR - .833 \ln R$

Subcategory II-2.

DV21. Nuttli (App. C-A)

$$\ln(v) = \begin{cases} -3.11 + 1.15m_b - 0.833 \ln [R^2 + \exp(-4.371 + 1.308\ m_b)]^{1/2} - 0.00122(R-1) & m_b \leq 4.4 \\ -8.29 +2.3\ m_b - 0.833 \ln [R^2 + \exp(-7.968 + 2.100\ m_b)]^{1/2} - 0.00122(R-1) & 4.4 < cm_b < 7.4 \end{cases}$$

7.3.3 Response Spectra

RS1 Modified Reg. Guide 1.60 (spectral shape anchored to PGA)
RS2 NBS, 1978 - ATC (spectral shape anchored to PGA)
RS3 Newmark and Hall (1982) (spectral shape anchored to PGA and PGV)
RS4 Bernreuter (1981a): Distance-weighted model

$$\ln(SA) = C_1 + C_2 I_o + C_3 R + C_4 \ln R$$

where SA = pseudo-absolute acceleration in cm/sec^2

Frequency (Hz)	C_1	C_2	C_3	C_4
25.0	2.35	0.55	-0.0025	-0.542
20.0	2.49	0.55	-0.0025	-0.565
12.5	2.84	0.56	-0.0026	-0.612
10.0	2.98	0.56	-0.0025	-0.605
5.0	2.87	0.56	-0.0026	-0.487
3.3	2.27	0.62	-0.0028	-0.433
2.5	1.60	0.65	-0.0030	-0.346
1.0	-1.21	0.816	-0.0038	-0.100
0.5	-3.19	0.886	-0.0041	0.061

RS5 Bernreuter (1981a) Magnitude-weighted model

$$\ln(SA) = C_1 + C_2 I_o + C_3 R + C_4 \ln R$$

Frequency (Hz)	C_1	C_2	C_3	C_4
25.0	2.67	0.59	-0.0007	-0.760
20.0	2.73	0.58	-0.0007	-0.761
12.5	3.04	0.57	-0.0007	-0.768
10.0	3.20	0.56	-0.0007	-0.775
5.0	3.84	0.52	-0.0007	-0.740
3.3	3.63	0.57	-0.0007	-0.762
2.5	3.34	0.57	-0.0007	-0.719
1.0	1.23	0.71	-0.0006	-0.637
0.5	-0.34	0.74	-0.0005	-0.536

7.4 QUESTIONS

Based on your opinion of the data and methods used to develop a model, the ability of a model to accurately reflect the attenuation and ground motion within a region, and any other information you deem appropriate to judge the models, please respond to the following questions using the included Questionnaire Reply Forms.

7.4.1 Peak Ground Acceleration

For each of the four regions and two magnitude scales,

Question 1. Among the peak ground acceleration models catalogued in Section 7.3.1, indicate the one model (or attenuation/ground motion pair) which you consider to be the most appropriate ground motion model, i.e., select the "best estimate" model for peak ground acceleration.

Question 2. For each of the seven subcategories (types) of peak ground acceleration models, I-1 through I-5, II-1, and II-2, select the one model within the subcategory which you consider to be most appropriate (Note: for subcategories I-1 through I-4, this should be a pair of models).

Question 3. For each of the seven subcategories, indicate a confidence level which you associate with that type of model.

Notes: (1) See the discussion of confidence level in Section 7.2

(2) For each region, magnitude scale pair, if $C_1, C_2, \ldots, C_7$ denote the confidence levels for the seven subgroups

- o any C_i can be zero
- o the sum of the C_i's should equal 1.0

Question 4. Indicate any ground motion models for PGA which were not included in the catalogue in Section 7.3.1 and which you consider worthy of consideration by the panel at a future time.

7.4.2 Peak Ground Velocity

For each of the four regions and two magnitude scales,

Question 5 Among the peak ground velocity models catalogued in Section 7.3.2, indicate the one model (or attenuation/ground motion pair) which you consider to be the most appropriate ground motion model, i.e., select the "best estimate" model for peak ground velocity.

Question 6 For each of the seven subcatagories of peak ground velocity models I-1 through I-5, II-1, and II-2, select the one model within the subcatagory which you consider to be most appropriate (Note: for subcatagories I-1 through I-4, this should be a pair of models).

Question 7 For each of the seven subcatagories, indicate a confidence level which you associate with that type of model. (See the Note after Question 3)

Question 8 Indicate any ground motion models for PGV which were not included in the catalogue in Section 7.3.2 and which you consider worthy of consideration by the panel at a future time.

7.4.3 Spectra

Response for each of the four regions and two magnitude scales,

Question 9. Among the response spectra models catalogued in Section 7.3.3, indicate the spectral shape model (or attenuation/spectra pair) which you consider to be the most appropriate response spectra model.

Question 10 For each of the response spectra models in Section 7.33, indicate a confidence level which you associate with that type of model (see the notes after Question 3).

Question 11 Indicate any response spectra models which were not included in the catalogue in Section 7.3.3 and which you consider worthy of consideration by the panel at a future time.

7.4.4 Random Variation

As discussed in Section 7.1, the standard deviation of the error associated with a model includes both a measure of the random variation in the GMP about its expected or average value as well as a measure of the adequacy of the model. It is important in doing the hazard analysis that only the random variation component be used when making the probability calculations. Thus, we need to elicit your opinions about the magnitude of the random variation associated with each of the ground motion parameters.

Since the GMP is a function of earthquake magnitude and distance, we are interested in the random variation in GMP conditional on magnitude and distance. Our hazard analysis assumes that the GMP random variation is independent of magnitude and distance as well as the site, although we do allow for regional variation by asking you to provide your estimates on a regional basis.

Since we will be modeling the random variation in the GMP by a lognormal distribution, we would like you to provide your estimates of the random variation either in terms of

- o the standard deviation of the lnGMP, σ
- o the coefficient of variation of the GMP, COV

Using Table 7.1, included in this Questionaire, for each of the GMP's and each of the four regions,

Question 12 Give your best estimate of the random variation (either σ or COV) in the GMP at a site.

Question 13 Give an interval which you believe, with a high degree of confidence, represents the possible range of σ or COV.

Question 14 Do you agree with our choice of the lognormal distribution to describe the random variation in the GMP's? If not, please indicate a distribution which is more appropriate.

7.5 Self-Rating

In our hazard analysis it will be necessary to combine the risks at a site based on the different ground motion models chosen by a panel member as well as combining over the the opinions provided by all panel members. Combining the risks estimate using the different models suggested by an individual member will be based on the confidence levels you provide. To combine over all the panel members we propose to use a weighted average procedure. Of course, this requires an appropriate set of weights.

Although there are several weighting schemes (e.g., equal weights, LLNL derived weights), the set of weights we propose to use is based on your appraisal, i.e., self- rating, of your expertise about the utility of ground motion models.

We recognize some of the weaknesses and difficulties in eliciting and using self-rating, however, most alternative weighting schemes are also subjective and involve some of the same problems as self-rating. Overall, we believe self-rating to be a viable means of developing weights for combining the results derived from your opinions about the ground motion models. Thus, we would like you to indicate your level of expertise with regard to assessing the utility of the ground motion models.

In appraising your level of expertise, we ask that you use a 1-10 scale where low values indicate a low level of expertise and high values a high level of expertise. An integer value is not necessary, although not more than one decimal place (e.g., 7.3) is appropriate.

Question 15. Please indicate your level of expertise with regard to assessing the utility of ground motion models.

Table 7.1
(Questions 12 and 13)

Parameter		Region: Northeast	Southeast	North Central	South Central
PGA	Best Estimate:				
	Confidence Bounds:				
PGV	Best Estimate:				
	Confidence Bounds:				

Spectra

PEAK GROUND ACCELERATION

		REGION							
		Northeast		Southeast		Northcentral		Southcentral	
		MMI	m_b	MMI	m_b	MMI	m_b	MMI	m_b
estion 1									
"Best Estimate" Model									
estions 2 and 3									
Intensity Based Models									
I-1. No Weighting									
	Models(1)	(,)	(,)	(,)	(,)	(,)	(,)	(,)	(,)
	Confidence								
I-2. Distance Weighting									
	Models(1)	(,)	(,)	(,)	(,)	(,)	(,)	(,)	
	Confidence								
I-3. Magnitude Weighting									
	Models(1)	(,)	(,)	(,)	(,)	(,)	(,)	(,)	
	Confidence								
I-4. Magnitude + Distance Weighting									
	Models(1)	(,)	(,)	(,)	(,)	(,)	(,)	(,)	(,)
	Confidence								
I-5. Semi-Empirical									
	Model								
	Confidence								
. Direct Models									
II.1. γ Variable									
	Model								
	Confidence								
II.2 γ K(M) Variable									
	Model								
	Confidence								

) For categories I-1 thru I-4, a ground motion model consists of (a) an intensity-attenuation relation and (b) a PGA site intensity relation.

B. PEAK GROUND VELOCITY

	REGION							
	Northeast		Southeast		Northcentral		Southcentral	
	MMI	m_b	MMI	m_b	MMI	m_b	MMI	m_b
Question 5								
"Best Estimate" Model								
Questions 6 and 7								
I. Intensity Based Models								
I-1. No Weighting								
Models[1]	(,)	(,)	(,)	(,)	(,)	(,)	(,)	(,)
Confidence								
I-2. Distance Weighting								
Models[1]	(,)	(,)	(,)	(,)	(,)	(,)	(,)	
Confidence								
I-3. Magnitude Weighting								
Models[1]	(,)	(,)	(,)	(,)	(,)	(,)	(,)	
Confidence								
I-4. Magnitude + Distance Weighting								
Models[1]	(,)	(,)	(,)	(,)	(,)	(,)	(,)	(,)
Confidence								
I-5. Semi-Empirical								
Model								
Confidence								
II. Direct Models								
II.1. γ Variable								
Model								
Confidence								
II.2 γ K(M) Variable								
Model								
Confidence								

(1) For categories I-1 thru I-4, a ground motion model consists of (a) an intensity-attenuation relation and (b) a PGV-site intensity relation.

Question 4 Additional Peak Ground Acceleration Models

Question 8 Additional Peak Ground Velocity Models

C. RESPONSE SPECTRA

	REGION							
	Northeast		Southeast		Northcentral		Southcentral	
	MMI	m_b	MMI	m_b	MMI	m_b	MMI	m_b
Question 9								
"Best Estimate" Model								
Question 10								
RS1. Reg. Guide 1.60								
Confidence								
RS2. NBS, 1978 - ATC								
Confidence								
RS3. Newmark-Hall								
Confidence								
RS4. Distance-Weighting								
Confidence								
RS5. Magnitude-Weighting								
Confidence								
RS6 Westermo, et al.								
Confidence								

Question 11 Additional Response Spectra Models

). RANDOM VARIATION

Questions 12 and 13		Northeast	Southeast	Northcentral	Southcentral
. Peak Ground Acceleration					
	Best Estimate				
	"Confidence" Bounds				
Peak Ground Velocity					
	Best Estimate				
	"Confidence" Bounds				
Response Spectra					
	Best Estimate				
	"Confidence" Bounds				

The four region columns are printed under the heading REGION.

Question 14

Is lognormal distribution an adequate description of random variation?
If no, what is a more appropriate distribution?

E. SELF RATING

Question 15

Self-Rating:

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A P P E N D I C E S

Appendix C-A: Nuttli's Letter
(January 24, 1983)

Appendix C-B: Trifunac's Letter
Regarding R
(January 18, 1983)

Appendix C-C: Campbell's Letter
Regarding R
(January 1, 1983)

APPENDIX C-A

OTTO W. NUTTLI
PROFESSOR OF GEOPHYSICS
P.O. BOX 8099, LACLEDE STA.
ST. LOUIS, MISSOURI 63156
(314) ~~[illegible]~~ 658-3124

January 24, 1983

FEB 4 REC'D

Dr. Dae H. Chung, L-95
Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA 94550

Dear Dan;

I am writing to offer my suggestions as to how to handle the attenuation problem in LLNL's sensitivity study of strong ground motion.

My recommendation is to use three different models, to determine the sensitivity of the site ground motion to different attenuation relations. Model 1 would be the one used two or three years earlier in the LLNL-TERA study for specific eastern nuclear power plant sites. There are two reasons for including this model: first, it will show the sensitivity to different source models in the two studies, as the attenuation relation will be the same for both; second, it is based on intensity data, which make up the bulk of eastern United States data, and thus is the most empirical (relies least on theoretical modeling) kind of attenuation relation. The problem is that we have to use data bases from other parts of the world, primarily the western United States, that relate M.M. intensity to ground acceleration, velocity and displacement, and we have good reason to suspect that these data are not directly applicable to the eastern United States.

Model 2 would be Ken Campbell's attenuation curves for strong ground motion for the central United States. These curves assume that the source excitation is the same for eastern and western earthquakes of a given magnitude, but that the anelastic attenuation is different for the two regions. The idea is similar to that employed by Algermissen and Perkins in constructing their hazard maps for the United States, and to that used by me in the 1979 report to the Waterways Experiment Station of the Corps of Engineers. One potential problem with Campbell's curves is the way he defines magnitude, i.e., M_L for M_L less than 6.5 and M_S for M_S greater than 6.5. The relations which I obtain for the eastern United States (spectral scaling paper to appear in April 1983 issue of BSSA) are:

$$M_S = 1.0\ m_b - 1.15 \qquad \text{for } m_b \le 4.5$$

$$M_S = 2.0\ m_b - 5.65 \qquad \text{for } 4.5 \le m_b \le 7.0.$$

For the eastern United States Bob Herrmann and I showed that $M_L = m_b$. In the East you seldom will have to deal with earthquakes of M_L greater than 6.5. Therefore my suggestion is to use M_L (or m_b) values with Campbell's curves.

Model 3 is one which has evolved from studies of Bob Herrmann and myself. The most recent published version is my paper in the Proceedings of the June 1982 Earthquake Microzonation Conference. The method uses empirical studies of mid-plate magnitudes and moments to establish spectral scaling relations, from which a scaling law for peak ground acceleration, velocity and displacement is derived. Frequency-dependent anelastic attenuation relations are obtained from measurements of eastern earthquakes by observatory-type instruments. The level of the attenuation curves is determined by existing central United States strong-motion data, as present in the Microzonation paper. Thus Method 3 is semi-empirical, semi-theoretical. Although I am not impartial and unbiased, I believe it represents the best existing set of strong motion relations for the East.

I don't believe it is advisable to attempt to distinguish between differences of anelastic attenuation in the craton region of the central and eastern United States and the accreted coastal-plain regions to the east and south of the Appalachian and Ouachita-Wichita Mountains. By attempting to consider this effect you would be introducing a refinement that has smaller consequences than those resulting from more basic uncertainties in the attenuation relations.

In the paper for the Microzonation meeting I presented my attenuation relations only in the form of sets of curves. In the past week I put them in equation form. Also, based upon material contained in my spectral scaling paper, I have more carefully considered the problem of minimum focal depth, which affects the ground motion at small epicentral distances. Included is a figure showing how the ground acceleration at near-source distances changes with focal depth for an $m_b = 5.0$ earthquake. Because we cannot possibly estimate focal depth for all the historical earthquakes, I suggest that in all cases you use the attenuation curves for minimum focal depth, as in the three figures included with this letter (for maximum acceleration, velocity and displacement). This is most conservative, in the sense that it will give the largest possible ground motions.

Please don't hesitate to call me if you have any questions, criticisms, suggestions, or such.

With best regards,

Sincerely,

Otto

Otto W. Nuttli

Enclosures

P.S. The equations and curves are an average for various rock and soil types. Probably they are most representative of a stiff or competent soil.

STRONG GROUND MOTION ATTENUATION RELATIONS
FOR THE CENTRAL UNITED STATES

Minimum Focal Depth

$$\log_{10} h_{min}\ (\mathrm{km}) = -0.949 + 0.284\ m_b \quad \text{for } m_b \leq 4.4$$

$$\log_{10} h_{min}\ (\mathrm{km}) = -1.730 + 0.456\ m_b \quad \text{for } m_b > 4.4$$

Q_o (quality factor at 1 Hz) = 1000; $Q(f) = 1000f^{0.3}$ (f = frequency)

Max-Acc = arithmetic average of peaks on 2 horizontal components

assumed: a_{max} has a frequency of 5 Hz
v_{max} has a frequency of 1.5 Hz
d_{max} has a frequency of 0.5 Hz

$$\log_{10} a_{max}\ (\mathrm{cm/sec^2}) = 1.69 + 0.25\ m_b - 0.833 \log_{10}\ r^2+h^2 - 0.00122\ (r-1) \quad \text{for } m_b \leq 4.4$$

$$\log_{10} a_{max} = 0.57 + 0.50\ m_b - 0.833 \log_{10}\ r^2+h^2 - 0.00122\ (r-1) \quad \text{for } 4.4 < m_b \leq 7.4$$

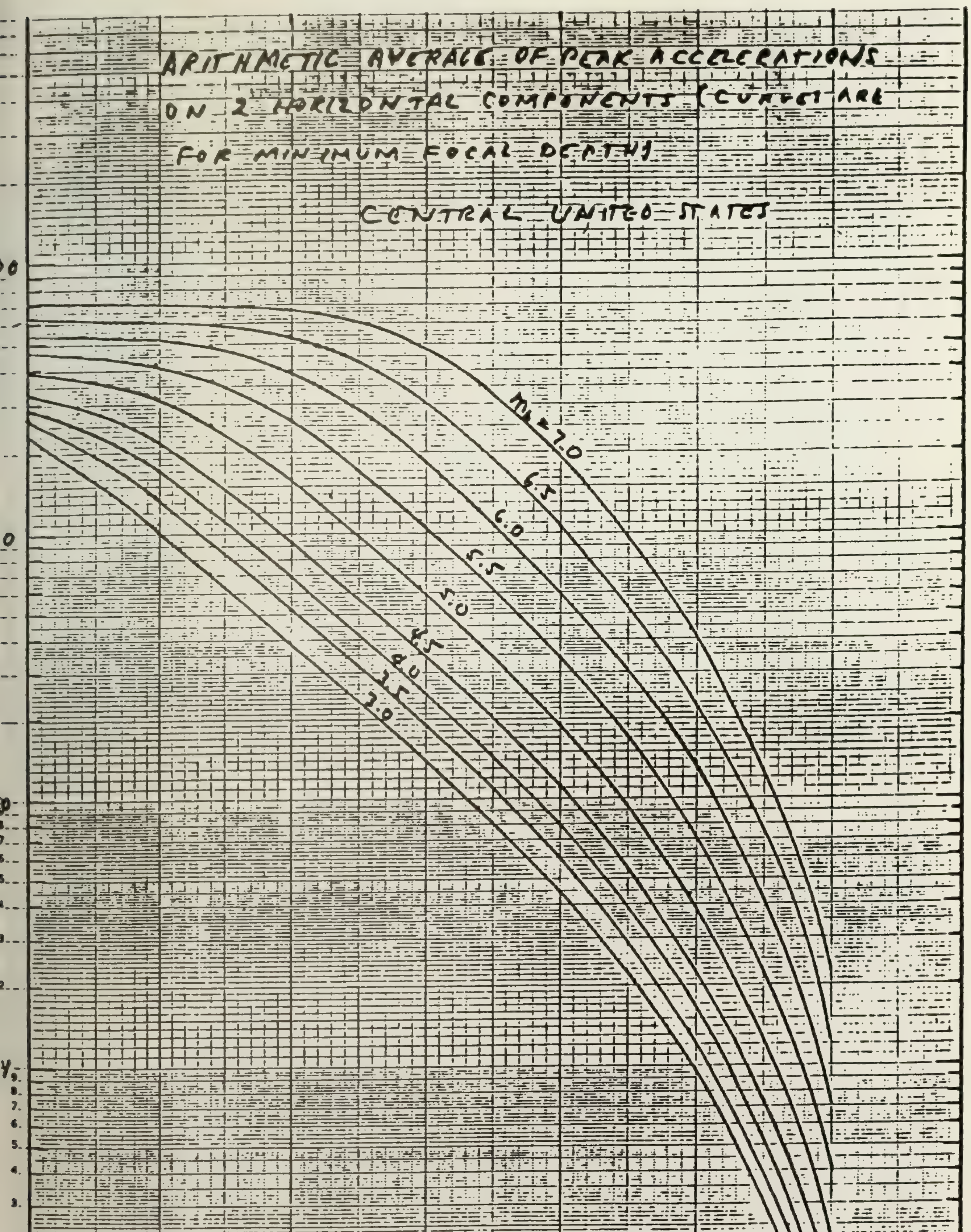
$$\log_{10} V_{max}\ (\mathrm{cm/sec}) = -1.35 + 0.50\ m_b - 0.833 \log_{10}\ r^2+h^2 - 0.000532\ (r-1) \quad \text{for } m_b \leq 4.4$$

$$\log_{10} V_{max} = -3.60 + 1.00\ m_b - 0.833 \log_{10}\ r^2+h^2 - 0.000532\ (r-1) \quad \text{for } 4.4 < m_b \leq 7.4$$

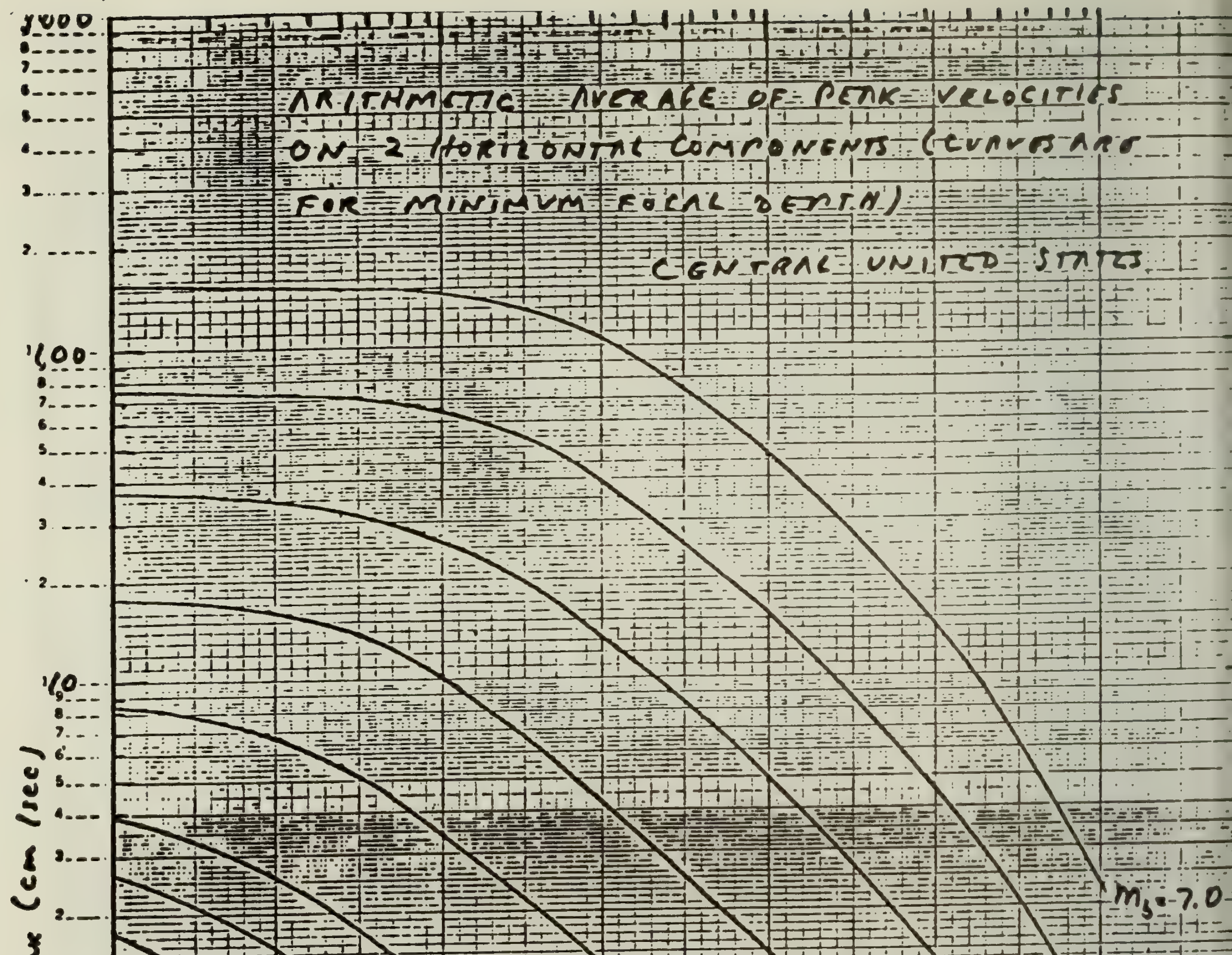
$$\log_{10} d_{max}\ (\mathrm{cm}) = -3.43 + 0.75\ m_b - 0.833 \log_{10}\ r^2+h^2 - 0.000244\ (r-1) \quad \text{for } m_b \leq 4.4$$

$$\log_{10} d_{max} = -6.81 + 1.50\ m_b - 0.833 \log_{10}\ r^2+h^2 - 0.000244\ (r-1) \quad \text{for } 4.4 < m_b \leq 7.4$$

where h = focal depth (in km) and r = epicentral distance (in km).

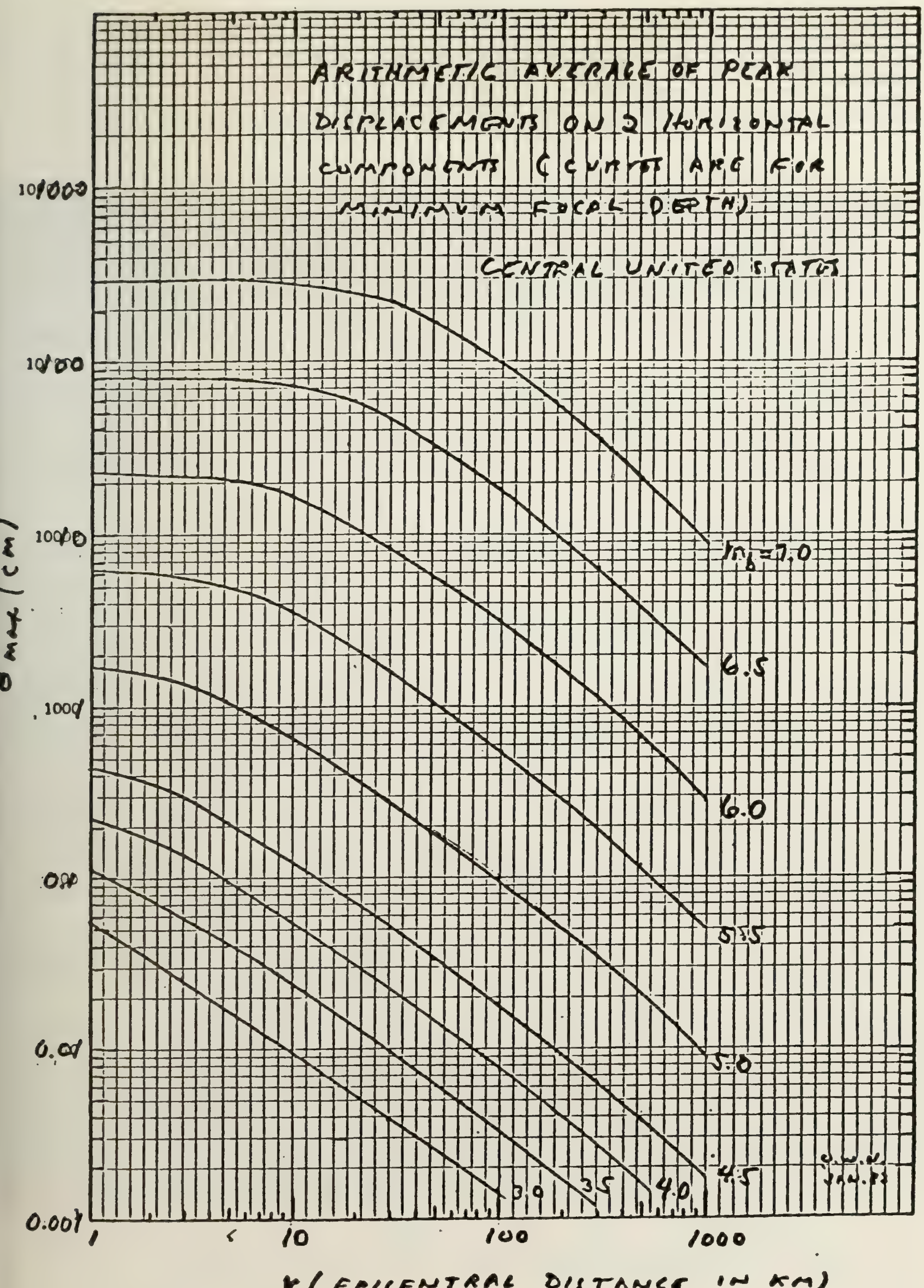


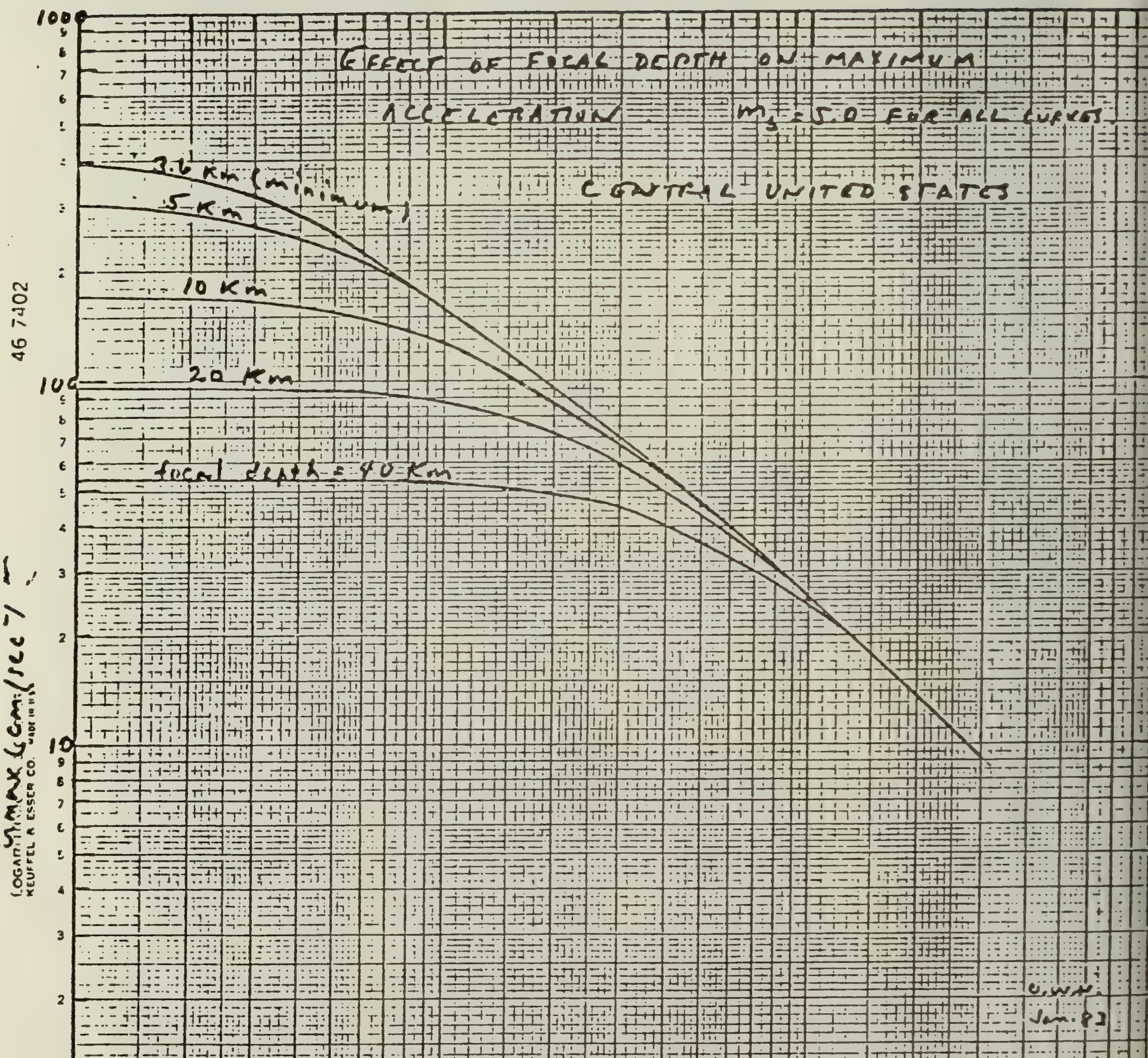
ARITHMETIC AVERAGE OF PEAK ACCELERATIONS
ON 2 HORIZONTAL COMPONENTS (CURVES ARE
FOR MINIMUM FOCAL DEPTHS)
CENTRAL UNITED STATES
mb=7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
O.W.N.
Jan 85
1
10



ARITHMETIC AVERAGE OF PEAK VELOCITIES ON 2 HORIZONTAL COMPONENTS (CURVES ARE FOR MINIMUM FOCAL DEPTH)
CENTRAL UNITED STATES
V_{max} (cm/sec)
1000
100
10
1
0.1
0.01
1
10
M_s=7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0

MODEL DATE


ARITHMETIC AVERAGE OF PEAK DISPLACEMENTS ON 2 HORIZONTAL COMPONENTS (CURVES ARE FOR MINIMUM FOCAL DEPTH)
CENTRAL UNITED STATES
m_b = 7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
O.W.N. JAN. 83
10.000
1.000
100
10
1.0
0.10
0.01
0.001
1
10
100
1000
d_{max} (cm)
r (EPICENTRAL DISTANCE, IN KM)



EFFECT OF FOCAL DEPTH ON MAXIMUM ACCELERATION
m_b = 5.0 FOR ALL CURVES
CENTRAL UNITED STATES
3.6 Km (minimum)
5 Km
10 Km
20 Km
focal depth = 40 Km
a_{max} (cm/sec²)
r (EPICENTRAL DISTANCE, IN KM)
O.W.N.
Jan. 83
46 7402
LOGARITHMIC
KEUFFEL & ESSER CO. MADE IN U.S.A.

APPENDIX C-B

UNIVERSITY OF SOUTHERN CALIFORNI

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SCHOOL OF ENGINEERING
DEPARTMENT OF CIVIL ENGINEERING

FEB 4 REC'D

January 18, 1983

Dr. Dae H. Chung
Lawerence Livermore Laboratory
University of California
Livermore, California 94550

Dear Dae,

As you requested I am enclosing my brief comments on the use of 'distance' in the papers by Joiner and Boore (1981) and Campbell (1981). Those are:

1. Joiner and Boore (1981) employ a definition of distance which is equivalent to $(R_o^2+ h^{*2})^{1/2}$ in the enclosed Figure 1. In their work h* is a 'measure' of the source depth selected to minimize the sum of the squares of the residuals. This definition of distance would be appropriate if an argument could be made that the peak ground motion comes from the portion of the fault surface which is at 'depth' h* and beneath A in Figure 1.

2. Campbell (1981) uses distance R_2 (in Figure 1) and a magnitude dependent 'coefficient' C(M) which physically resembles h*. This is also fitted to the data to minimize the sum of the residuals squared.

Assume we have recorded three peak accelerations and we wish to plot those versus same distance R as in Figure 2. In a typical case (say Imperial Valley 1979 data) I interpret Campbell's work to plot these data points as crosses (+) in Figure 2. Joiner and Boore (1981) definition would lead to the peaks plotted as circles (o) in Figure 2 (assuming that somehow we know h*). Assuming on the other hand, that we wish to plot those peak accelerations versus distance R_1, which is a distance to a 'center' of the fault surface we would get the points shown by asterisks,(Figure 2). It is obvious from the geometry of Figure 2 that $R_o<R_1, R_2<R_1$ and $(R_o^2+ h^{*2})^{\frac{1}{2}}<R_1$. Since we do not know a priori which part of the fault will contribute most to the peak ground motions, unless $L>>R_1$ it would seem reasonable to use some definition (in the mean) close to R_1. This effect is of course significant only for small R_1 and as $R_1\to\infty$ all definitions of distance become indistinguishable. Therefore I believe that Joiner and Boore (1981) as well as Campbell (1981) have a tendncy to underestimate peak amplitudes of ground motion for small R. This is seen from sketch in Figure 2.

I am taking the liberty of sending these comments to Boore and Campbell directly. I hope they can examine them and suggest wether I have erred in my interpretation of their results.

Please let me know if you feel that these comments are not clear and wether there are additional aspects of interest that I did not discuss.

Sincerely,

M. D. Trifunac

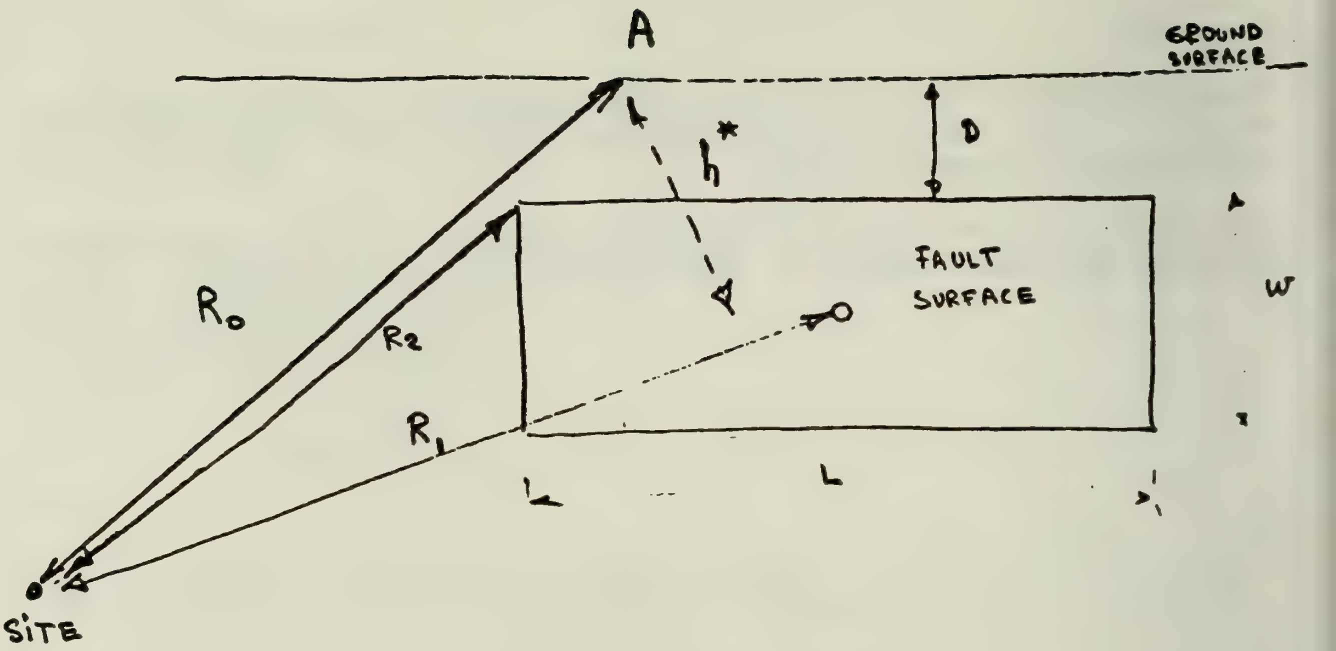

Figure 1

BOORE & JOINER (1981) use $r = (d^2 + h^2)^{1/2}$ where "d is the closest distance from the recording site to the surface projection of the fault rupture." This corresponds to R_0 in Figure 1

Campbell (1981) uses "shortest distance between the station and the fault rupture surface"... I interpret this to correspond to distance like R_2 in Figure 1

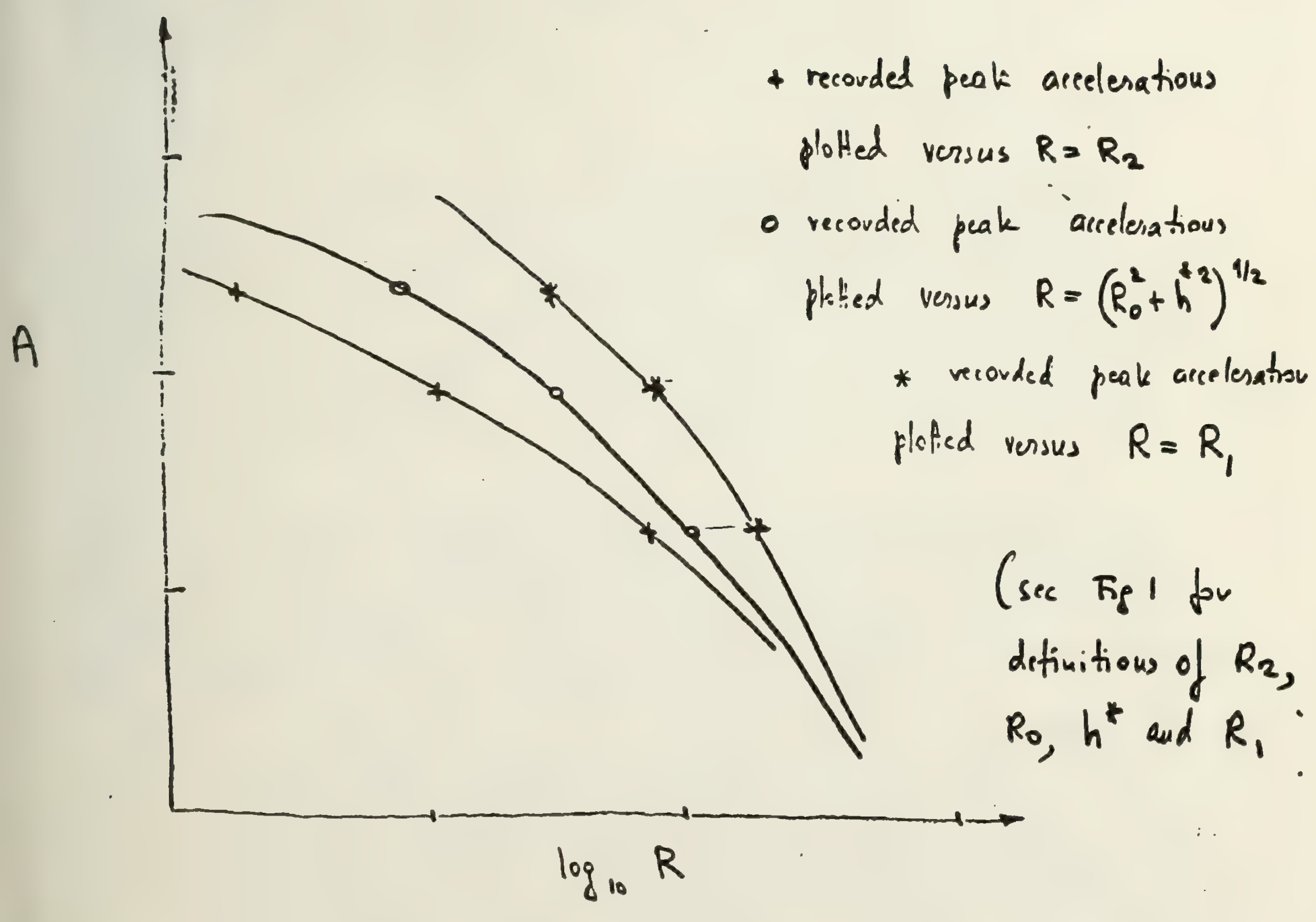
A
$\log_{10} R$
+ recorded peak accelerations plotted versus $R = R_2$
o recorded peak accelerations plotted versus $R = (R_0^2 + h^{*2})^{1/2}$
* recorded peak acceleration plotted versus $R = R_1$
(see Fig 1 for definitions of R_2, R_0, h^* and R_1.

Figure 2

APPENDIX C-C

TERA

BERKELEY · DALLAS · BETHESDA · BATON ROUGE · NEW YORK · DENVER · LOS ANGELES · VALLEY FORGE

February 3, 1983

FEB 8 REC'D

Dr. Dae H. Chung, L-90
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, California 94550

Dear Danny:

I would like to take this opportunity to respond to Dr. Trifunac's letter of January 18 regarding the use of "distance" in strong-motion scaling relationships. He claims that the use of shortest distance between the recording site and the fault rupture surface (used by Campbell, 1981) has a tendency to underestimate peak amplitudes of strong ground motion for small distances. He infers from his Figure 2 that this could be avoided by defining distance as the distance from the recording site to the center of the fault surface. This latter definition is preferred by Dr. Trifunac, since it is not known in advance which part of the fault will contribute most to peak ground motions.

Although we may not know in advance where the peak motions will come from, there is considerable evidence to suggest that closest distance to the fault rupture (R_2) is a more appropriate measure than distance to the center of fault rupture (R_1) for characterizing and predicting the scaling properties of strong-motion parameters. In fact, scaling relationships based on R_1 as they are commonly used will lead to overestimation of peak parameters in some cases. Arguments in support of these statements are as follows:

(1) The use of closest distance to the fault rupture is consistent with the definition of distance in seismic design scenarios. For lack of more detailed information, design earthquakes are always hypothesized to rupture that portion of the causative fault closest to the site and distance is always measured from the closest point of this rupture. This is identical to the definition of distance used to develop the scaling relationship of Campbell (1981). The degree to which this distance is inappropriate in both past and future earthquakes is reflected adequately in the uncertainty associated with the prediction (the standard error of estimate) and may be properly accounted for by using a prediction based on a percentile greater than 50 percent (the median).

(2) With the realization that the portion of the fault responsible for the peak motion at a recording site is most likely closer than the center of rupture, taken with the way design earthquakes are hypothesized, the use of distance to the center of fault rupture will result in overestimation of strong-motion parameters in situations where the fault rupture is adjacent to the site. There are many fault rupture configurations where the fault can rupture adjacent to the site. For all but one of these configurations, the center of the fault rupture will not be associated with the

closest portion of the rupture. In fact, for very large events, the center of rupture could be tens of kilometers further away than the closest point. The inevitable assumption for design purposes that the closest approach of the fault zone represents the center of rupture characterizes only one extremely rare rupture configuration. Coupled with the realization that distances to the center of rupture used in the development of the scaling relationships would be based on a random selection of such rupture scenarios, this inevitably leads to the overestimation of predicted values for typical design scenarios. To properly account for this discrepancy, distance should more appropriately be taken as the average distance to the center of all possible rupture configurations that lead to rupture adjacent to the site.

(3) The analysis of peak acceleration has shown that distances measured to single fixed points on the fault rupture surface are statistically inferior to those measured to the closest point on the fault. In the case of the 1979 Imperial Valley earthquake, distance scaling relationships based on closest distance to the rupture were found to have substantially lower standard errors than those based on any single fixed point on the fault, including the center of rupture and the epicenter. Multiple regression analyses for the Campbell (1981) dataset have also demonstrated that substantially lower standard errors are obtained when closest distance is used rather than epicentral or hypocentral distance.

(4) Earthquake modeling studies of recent earthquakes indicate that there are multiple patches of rupture (i.e., asperities) on the fault that contribute to strong ground motion and that those patches nearest the recording station tend to dominate the motion at that station. This would tend to favor closest distance to the fault rupture over distance to the center of rupture as the appropriate distance measure to use for scaling purposes.

It must be emphasized that, in order for these arguments to hold, one must use the closest distance to the hypothesized fault rupture when using the relationship of Campbell (1981), or any other relationship based on closest distance, to predict ground motion for either deterministic or probabilistic analyses. The use of epicentral or hypocentral distance with such a relationship in probabilistic analyses will lead to the underestimation of peak amplitudes for a given return period. However, if the proper distance measure is used, then the use of such a relationship can appropriately lead to smaller probabilistic estimates because of the smaller standard error associated with the expression.

In conclusion, Dr. Trifunac's simple argument is not appropriate in light of the known characteristics of strong ground motion and the way in which seismic design scenarios are formulated. Closest distance to the fault rupture surface does represent a realistic and appropriate means of characterizing distance for the development of strong-motion scaling relationships. I hope this discussion clarifies the confusion that developed at the strong-motion panel meeting regarding the appropriate definition of distance. If there are any more questions, please feel free to give me a call.

Sincerely,

Kenneth W. Campbell

KWC:cas

cc: Dave Boore
Leon Reiter
M. D. Trifunac

FIFTH QUESTIONNAIRE - FEEDBACK QUESTIONNAIRE ON

ZONATION AND SEISMICITY (Q5)

Feedback Questionnaire on Zonation and Seismicity

1. Introduction

This document constitutes the last step in LLNL elicitation process in finalizing the seismic zonation and the seismicity parameters of the Eastern United States (EUS). In the feedback meeting of December 13 and 14, 1983, held in Reston, Virginia, with representatives of the NRC, LLNL and the seismicity panel members, the details of the methodology were presented by LLNL. The Panel was given the opportunity to discuss the generic assumptions made by LLNL and to review the use of the experts' zonation and seismicity data. These discussions resulted in an improved understanding of the experts' data and of the methodology. As a result, several items have been identified as requiring clarification, modification, improvement or simply updating.

First, some minor errors in the interpretation of the experts' inputs and minor errors of interpretation of the questions in questionnaire Q1 (zonation questionnaire) and Q2 (seismicity questionnaire) were identified. For example, a change in the system of indexing regions by LLNL led to confusion and errors in the assignment of the regional self weights. This trivial error, which has little impact on the results, has been corrected. Another example is the way some experts interpreted the extent of the domain of validity of their recurrence relationships, in effect confusing the upper magnitude cutoff with the upper limit of the magnitude range within which their recurrence law is valid. This less trivial problem is discussed in Section 3.1 of this document.

Second, some more fundamental items were identified which require some modifications to improve the methodology. One item is the treatment of the recurrence relationship outside its domain of validity given by the experts. Another issue is the method used to simulate the recurrence models which does not account for correlation between the a's and b's in the linear (or bi-linear) models for the recurrence relationship.

And finally, some theoretical problems of more philosophical nature dealing with the meaning and the interpretation of self weights.

In Sections 2 to 5 of this document, each of these items is discussed with an emphasis on clarification and their consequences on the hazard calculation and uncertainty. These sections introduce the questions posed in Section 6, be it to clarify a point, update or modify a set of data or to elicit your opinion on items not discussed in the previous questionnaires.

2. Zonation Maps

In this part of the feedback elicitation process we are only concerned with the possible updating of the seismic source zone configurations. For this task, we would ask you to critically review your answers to the questionnaire on zonation (Q1) and modify your zonation maps as you see fit. The definition and assumptions necessary to perform this task are the same as the ones of Q1 and for more details you should refer to that document.

A variety of reasons may lead you to consider revising a zonation map, including:

- o You may have some new scientific information which may lead you to a different interpretation from the one derived at the time of answering Q1. This could include minor revisions to the original best estimate zonation map of Q1 as well as revised alternative maps or even entirely new best estimate maps and/or alternative maps.

- o The presentations and discussions which took place at the feedback meeting of December 13 and 14, 1983 may have modified your understanding of the seismicity zonation structure for a given part of the EUS.

- o Your responses to Q1, when interpreted by LLNL, lead to results which you do not consider plausible.

Please note that Tables A1 and A2 are an integral part of the zonation maps, since they are used to generate all the possible maps for the seismicity

zonation of the EUS. You are therefore encouraged to critically review your responses in Tables A1 and A2 in Q1. As a reminder, Table A1 gives the level of confidence in the existence of each zone. Therefore, for a zone with level of confidence less than one, there is the possibility that the area of the EUS defined by that zone will be part of another zone. This replacement or "Host" zone is also specified in Table A1.

Table A2 includes your uncertainty in the boundary shape of a zone or a cluster of zones. It includes a list of the zones or cluster of zones which have an alternative boundary shape and your level of confidence associated with each shape.

3. Seismicity Parameters

3.1 Magnitude Recurrence Modeling

As a consequence of the constructive discussion at the feedback meeting, we are making some modifications in the magnitude recurrence modeling which, we believe, will improve the methodology. These modifications involve the treatment of the recurrence relationship at the lower and upper ends of the domain of validity of the linear (bi-linear) model you provided for each zone.

Originally, at the lower magnitudes, if the lower endpoint of validity M_{LB} was equal to M_o, the minimum magnitude, the value of the magnitude recurrence relation at M_o, i.e., the value of $\log_{10} N_{Mo}$, was based on the average of

- $\log_{10} \lambda_o$
- $a + b\, M_o \equiv a + b\, M_{LB}$

given the two separate inputs λ_o, the expected number of earthquakes with magnitudes greater than or equal to M_o, and the coefficients (a,b) of the linear model. If $\log_{10} \lambda_o < a + b\, M_o$, then λ_o was not used. In response to the discussion of the feedback meeting, we plan to modify this to use only the linear magnitude recurrence model. Thus, when $M_o = M_{LB}$ we will not use your inputs about λ_o but only the magnitude recurrence equation a + bm.

When $M_0 < M_{LB}$, we will continue to model the recurrence relationship as we have previously, i.e, at M_0

$$\log_{10} N_{M_0} = \begin{cases} \log_{10} \lambda_o & \text{if } \log_{10} \lambda_o > a + b\, M_{LB} \\ a + b\, M_{LB} & \text{if } \log_{10} \lambda_o < a + b\, M_{LB} \end{cases}$$

and for $M_0 < m < M_{LB}$ we model N_m as a quadratic polynomial function of m. The resulting magnitude recurrence models are shown in Figure 3.1.1

A point of possible concern arises when $M_0 < M_{LB}$ and

$$\log_{10} \lambda_o < a + b\, M_{LB}.$$

This combination, as can be seen in Figure 3.1.1, suggests that no earthquakes with magnitudes between M_0 and M_{LB} are expected to occur.

If this is an unacceptable description of the seismicity for a given zone, it is necessary for you to make some adjustments in your seismicity parameters. Specifically, two possible adjustments might be based on

- o reconsidering the estimates of λ_0
- o reconsidering the values of the coefficients (a,b) and domain (M_{LB}, M_{UB}) of validity of the linear model a + bm.

At the high magnitudes, our initial treatment of the recurrence model was based on the philosophy that your linear model a + bm would not be changed over the domain of validity (M_{LB}, M_{UB}). Thus, the only adjustments in the recurrence model were made for $m > M_{UB}$ when M_U, the upper magnitude cutoff, was greater than M_{UB}. If that occurred, then the model for N_m for $M_{UB} < m < M_U$ is

$$N_m = \alpha\, e^{\beta m}(M_U - m)^2 \tag{3.1}$$

which satisfies the condition that $N_{M_U} = 0$. This adjustment is illustrated in

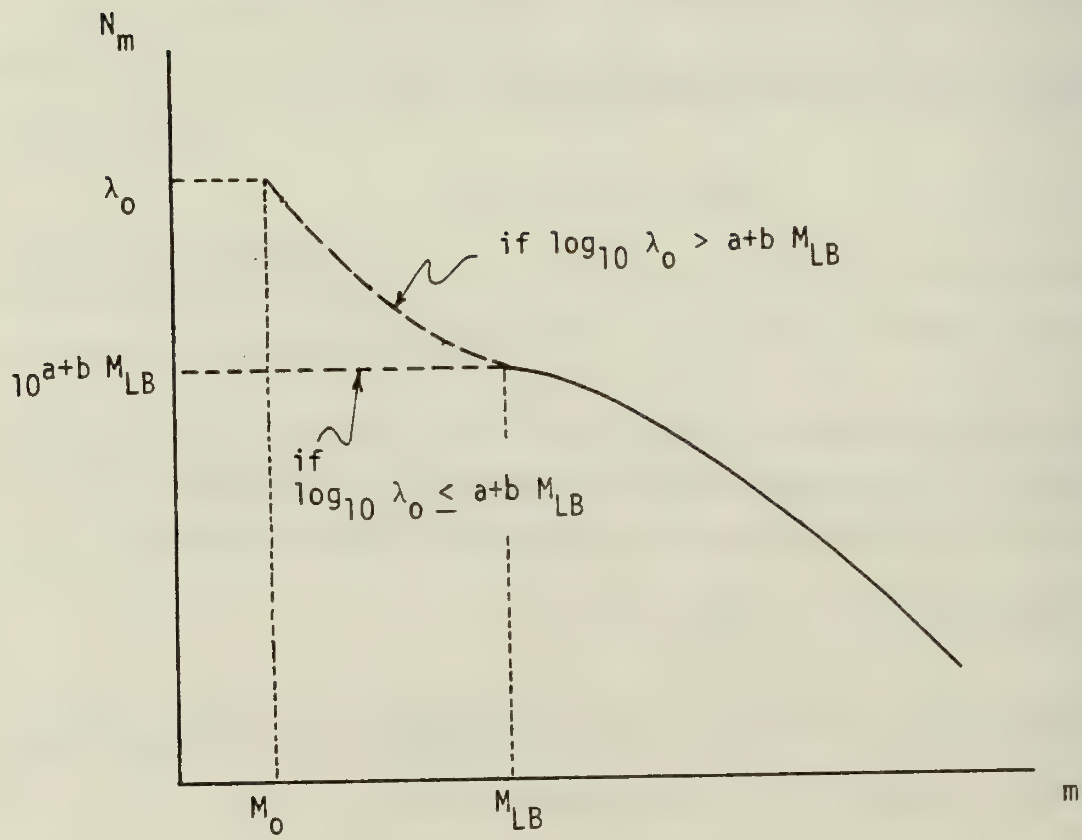

Figure 3.1.1 Magnitude Recurrence Models When $M_o < M_{LB}$

Figure 3.1.2. One consequence of modeling the recurrence relationship in this way is that the expected number of earthquakes in some magnitude interval $(m, m + \Delta)$ may be less than the expected number for a comparable interval at a higher interval $(m', m' + \Delta)$ where $m' > m$. This is illustrated in Table 3.1.1

In this illustration $M_{UB} = 7.5$. If $M_U = 7.75$, then, based on the LLNL method, the expected number of earthquakes with magnitudes between (7.5, 7.75) is 0.00069. On the other hand, the expected number with magnitudes (7.25, 7.5) is less, i.e., 0.00047. If $M_U = 7.5$, the expected number of earthquakes with magnitudes (7.25, 7.5) is .00116, again greater than the expected number .00079 in the preceding interval (7.0, 7.25). The same phenomena will occur if $M_U > M_{UB}$ and the adjustment in Equation (3.1) is used. Figure 3.1.3, although not to scale illustrates how the expected number increases in the last interval (7.25, 7.5) using the LLNL model.

An alternative model, suggested at the feedback meeting and described in [1] and [2], is based on modeling earthquake magnitudes as truncated exponential random variables with range (M_0, M_U). Without going into the mathematical details, the model for the logarithm of the expected number N_m of earthquakes with magnitude greater than or equal to m can be expressed as

$$\log_{10} N_m = \log_{10} N_0 + \beta M_0 \log_{10} e - \log_{10} \left(1-e^{-\beta(M_U-M_0)}\right) + \log_{10} \left(1-e^{-\beta(M_U-m)}\right)$$

$$-\beta m \log_{10} e \qquad (3.1.2)$$

where N_0 is the expected number of earthquakes with magnitudes greater than or equal to M_0 and β is the parameter of the exponential distribution. This

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[1] Weichert, D. H., Estimation of the Earthquake Recurrence Parameters for Unequal Observation Periods for Different Magnitudes, Bulletin of the Seismological Society of America, Vol. 70, No. 4, pp 1337-47, Aug. 1980.

[2] Cornell, C. A., Engineering Seismic Risk Analyses, Bulletin of the Seismological Society of America, Vol. 58, No. 5, pp 1583-1606, Oct. 1968.

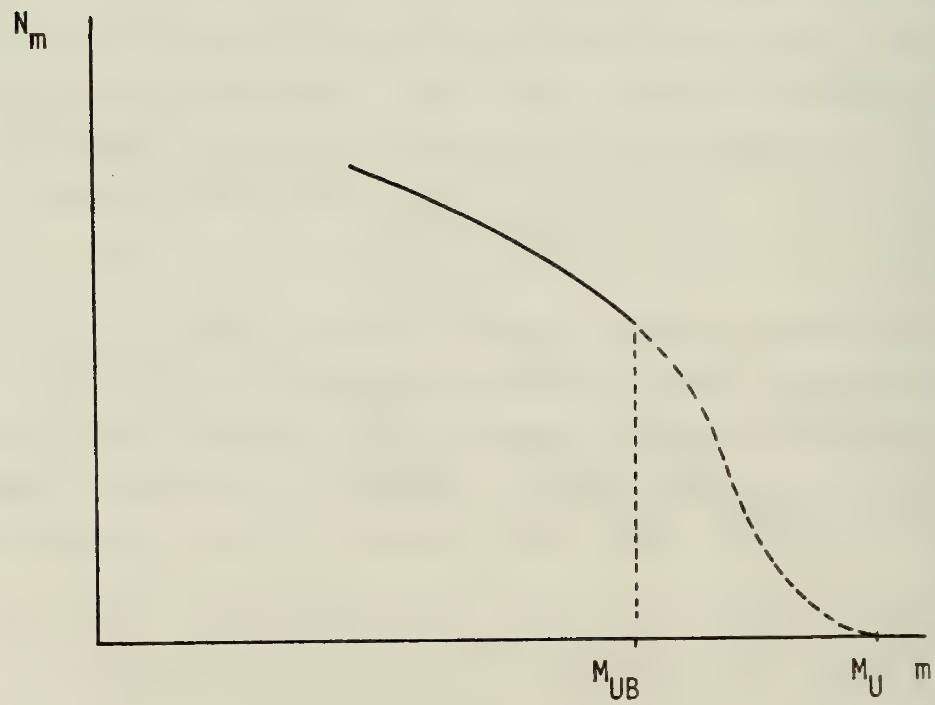


Figure 3.1.2 Adjustment in Recurrence Model When $M_U > M_{UB}$

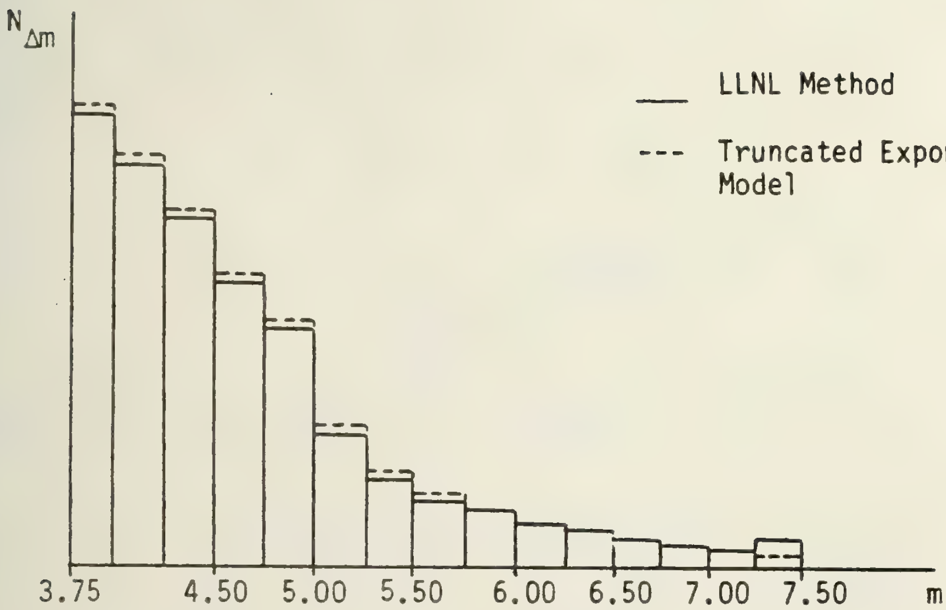


Figure 3.1.3 Estimates of the Expected Number of Earthquakes With Magnitudes in a Subinterval (Δm = .25) (Not to Scale)

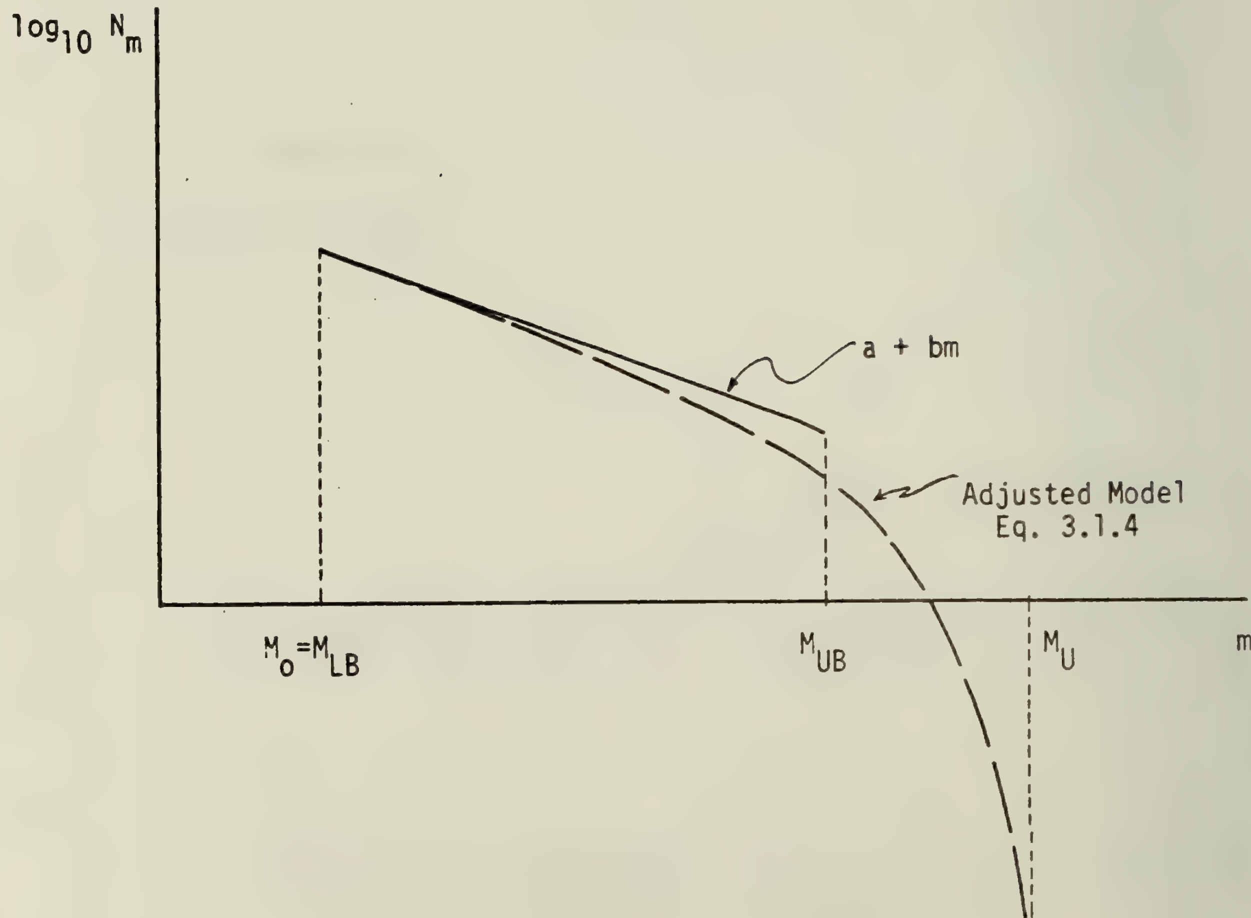


Figure 3.1.4 Truncated Exponential Model

relationship can be treated as an adjusted linear model by equating the linear model with Equation (3.1.2) at a point. Choosing that point to be $m = M_o$ gives

$$(3.1.3) \quad a + b\,M_o = \log_{10} N_o$$

Thus, Equation (3.1.2) can be rewritten in the form

$$\log_{10} N_M = a + b\,m + \log_{10}\left(1 - e^{-\beta(M_U - m)}\right) - \log_{10}\left(\left(1 - e^{-\beta(M_U - M_o)}\right)\right) \tag{3.1.4}$$

where now $\beta = -b \log_{10}^{-1} e$. The adjusted model is shown in Figure 3.1.4.

One advantage of this model is that the expected number of earthquakes in a magnitude interval will be monotone decreasing, as illustrated in Table 3.1.1 and Figure 3.1.3. However, it does adjust, slightly, the linear model $a + bm$ in the domain of validity M_{LB}, M_{UB}. As you can see for the example in Table 3.1.1, the expected number $N_{\Delta m}$ in an interval of low magnitudes increases slightly under this model. For example, for the magnitude interval (4.25, 4.50), based on the linear model (LLNL model), the expected number is .23536, whereas for the revised model (truncated exponential model) the expected number is .23547.

Although we have described this alternative assuming $M_o = M_{LB}$, if you choose to have us use the truncated exponential model we will make an adjustment if $M_o < M_{LB}$. In that case, because of the adjustment we make for $M_o < m < M_{LB}$, we will use the truncated exponential model for $m > M_{LB}$.

In summary, we propose to have you select between these two alternative ways of modeling the magnitude recurrence relationships:

A. LLNL Model

Case 1: $M_o = M_{LB}$ and $M_{UB} = M_{UU}$, i.e., the linear (piecewise linear) model is applicable for all m and upper magnitude cutoffs M_U. Use the linear model $a + bm$ without adjustment.

TABLE 3.1.1

Estimates of the Expected Number of Earthquakes Based on a Linear Model with a = 3.59, b = -0.9, M_{LB} = 3.75, M_{UB} = 7.5

	LLNL Model		Truncated Exponential Model	
M	N_m	$N_{\Delta m}$	N_m	$N_{\Delta m}$
3.75	1.64059		1.64059	
4.00	.97724	.66335	.97696	.66363
4.25	.58210	.39514	.51866	.39530
4.50	.34674	.23536	.34619	.23547
4.75	.20654	.14020	.20594	.14025
5.00	.12303	.08351	.12239	.08355
5.25	.07328	.04975	.07262	.04977
5.50	.04365	.02963	.04298	.02964
5.75	.02600	.01763	.02532	.01766
6.00	.01549	.01051	.01480	.01052
6.25	.00923	.00626	.00854	.00626
6.50	.00550	.00373	.00481	.00373
6.75	.00327	.00223	.00258	.00223
7.00	.00195	.00132	.00126	.00132
7.25	.00116	.00079	.00047	.00079
7.50	.00069	.00047		.00047
7.75		.00069		

Case 2: $M_o < M_{LB}$ or $M_{UB} < M_{UU}$, i.e., the linear model is applicable for $M_{LB} < m < M_{UB}$.

- If $M_o < M_{LB}$, set $N_{M_o} = \lambda_o$ and model N_m as a quadratic polynomial in m for $M_o < m < M_{LB}^{o}$

- For $M_{LB} < m < M_{LB}$, use the linear model a + bm

- If $M_{UB} < M_{UU}$, for any $M_U > M_{UB}$, model N_m by

$$N_m = \alpha e^{\beta m}(m - M_U)^2$$

  for $M_{UB} < m < M_U$.

B. Truncated Exponential Model

Case 1: $M_o = M_{LB}$
Use the adjusted model, Equation 3.1.4, for all $M_o < m < M_U$.

Case 2: $M_o < M_{LB}$

- Set $N_{M_o} = \lambda_o$ and model N_M as a quadratic polynomial in m for $M_o < m < M_{LB}$.

- Use the adjusted model, Equation 3.1.4, for all $M_{LB} < m < M_U$.

3.2 (a, b) Relationship and Uncertainty

Two issues, identified at the feedback meeting, relative to the estimates of the coefficients in the recurrence model which should be addressed in the final phase of the elicitation process are:

- The ranges of uncertainty in (a, b) and their effects on the range of uncertainty in N_M, the expected number of earthquakes with magnitude greater than or equal to m.

o How LLNL treats your uncertainty in (a, b), specifically the fact that the estimates are treated as if they are independent.

With regard to the first issue, this may not be a problem. However, we feel it is appropriate to make you aware of the implications of uncertainties in a and b. Specifically, we want to make sure that you are cognizant of how changes in a and b translate into variations in N_M, the expected number of earthquakes. To illustrate the effect of uncertainty in (a, b) assume a linear recurrence model,

$$\log_{10} N_m = a + bm$$

and

$$N_m = 10^a \, 10^{bm}$$

For simplicity, assume further that the uncertainty bounds are symmetric, i.e., $(a_L, a_U) = \hat{a} \pm \Delta a$ and $(b_L, b_U) = \hat{b} \pm \Delta b$. The range of uncertainty in N_m at any m can be represented by $(\frac{1}{f} N_m^0, f\, N_m^0)$ where

$$N_m^0 = 10^{\hat{a} + \hat{b}m}$$

is the best estimate and

$$f = 10^{\Delta a + \Delta bm}$$

is the factor of uncertainty, which varies with m. For example, if Δa = 1.2 and Δb = 0.2,

$$f(m = 3.75) = 89$$
$$f(m = 6.25) = 282$$

That is, the uncertainty in N_m ranges from a factor of 89 to 282 over the range of magnitude (3.75, 6.25).

If you have not considered the effect of the uncertainty in (a, b) on uncertainty in N_m in your response to Q2 we would encourage you to consider it as you review your estimates of seismicity and your uncertainty in these estimates as represented by the bounds, (a_L, a_U) and (b_L, b_U).

With regard to the treatment of your best estimates of a, b and your uncertainty about these coefficients in the magnitude recurrence model, up to now we have treated your level of knowledge about these coefficients as independent. We would like to offer two additional approaches to handle the joint uncertainty in estimating a and b which introduce correlation between these estimates. To do this, consider the following interpretation of how the uncertainty analysis is handled when your estimates of a and b are treated as independent.

Given your best estimates $\hat{a}$, $\hat{b}$ and bounds (a_L, a_U) and (b_L, b_U) the uncertainty analysis is based on treating the coefficients a, b as random variables with probability distributions based on the best estimates and bounds. Treating a, b as well as other inputs, e.g. M_U, maps, as random produces a probability distribution on the hazard which describes the corresponding uncertainty in the hazard due to your uncertainty in the zonation and seismicity. Let $F(a; \hat{a}, a_L, a_U)$ and $G(b; \hat{b}, b_L, b_U)$ denote the probability distributions for the intercept and slope respectively. Another distribution we can consider is the distribution of b given a value, say a_0, for a. Let $G(b|a_0)$ denote this distribution. This distribution would represent your level of knowledge about b corresponding to an intercept a_0. Since your estimate of the most likely value of b or uncertainty about b could change for each a_0, this conditional distribution could change with a_0. However, treating a and b as independent means that $G(b|a_0)$ is the same for all a_0 and

$$G(b|a_0) = G(b; \hat{b}, b_L, b_U)$$

Stated yet another way, independence of a and b is saying that your best estimate of b and uncertainty in b is the same for all values of the intercept. Graphically the relationship between a and b when, they are treated independently, is described by the set of possible magnitude recurrence models for different intercepts, as shown in Figure 3.2.1 for two values of a, a_U and a_0. Notice that the upper bound (best estimate, lower bound) models are parallel for all values of a.

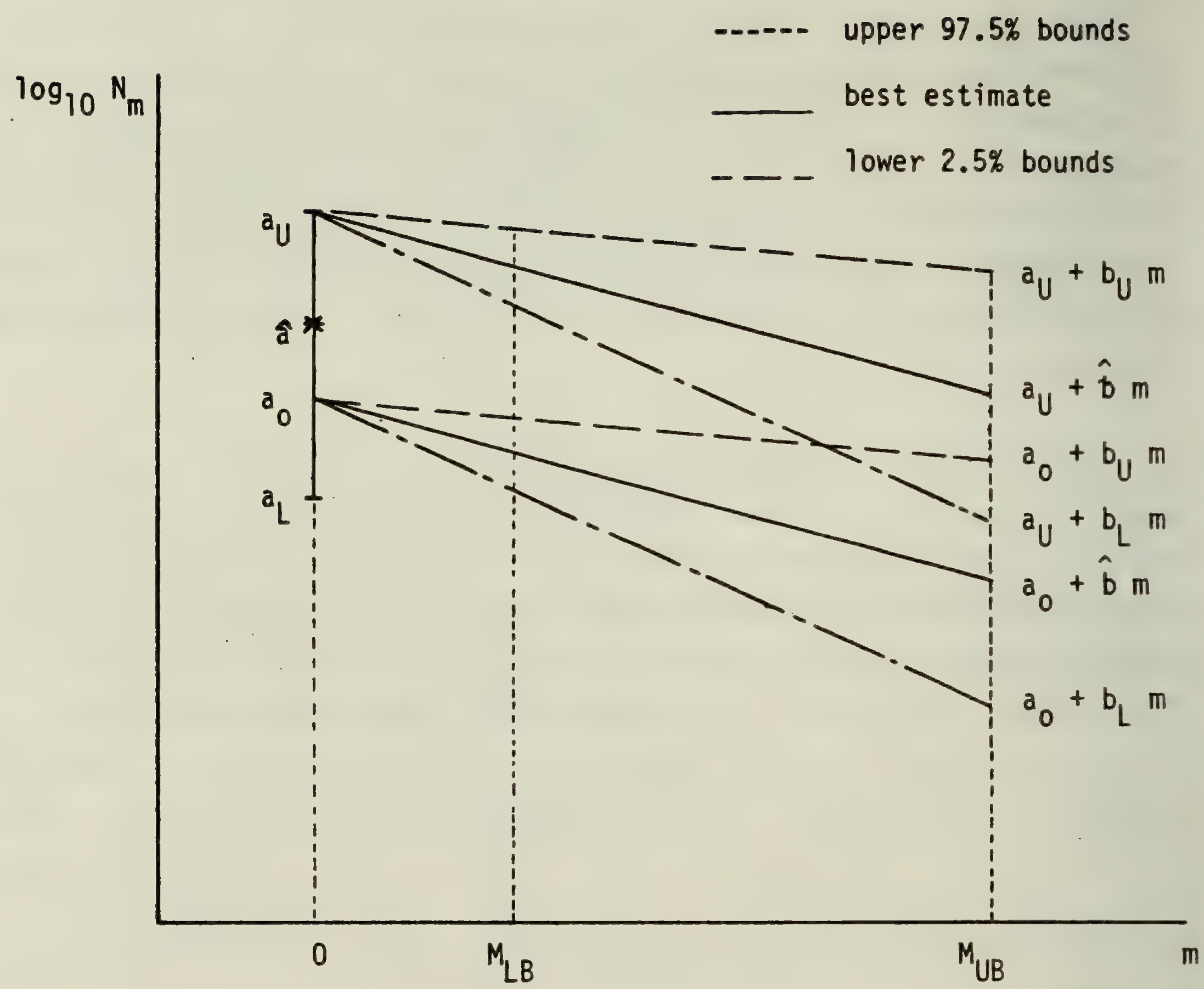


Figure 3.2.1 Range of Recurrence Models, Given a_U and a_o, When Estimates of a and b are Treated as Independent.

Some of you felt that independence of a and b is not the best model, however, it is difficult to assess the relationship (correlation) between these coefficients. Thus, we would like to offer two alternatives which impose some correlation but which use only the best estimates and bounds you already provided. Neither alternative requires additional inputs. We recognize that none of the alternatives are ideal. Also, the last alternative is very special and will only be an alternative for some of you. However, we will ask you to choose one of the approaches as the method for handling your estimates of the coefficients a, b. Note that in the two alternatives presented below (alternatives 2 and 3), the variation in the recurrence law is less than when a and b are independent (alternative 1), since the range of equations used in alternatives 2 and 3 is a subset of the range used in alternative 1.

Three ways of handling the relationship between your estimates of the coefficients a, b are:

1. <u>(a, b) are independent</u>

This method has been described in the introductory paragraphs. It assumes that the uncertainty distribution for b, <u>given a</u>, is the same for all a. Thus, the correlation between a and b is zero.

2. <u>(a, b) are "partially" negatively correlated</u>

This method is based on interpreting the model

$$\log_{10} N_m = \hat{a} + \hat{b}m$$

derived from your best estimates $\hat{a}$, $\hat{b}$ as representing your best estimate of $\log_{10} N_{M_{UB}}$ at the upper bound of the domain of validity of the model.

With this "interpretation" of your inputs, consider the following models for your estimates of a and b. As for the independence case, $F(a; \hat{a}, a_L, a_U)$ is the uncertainty distribution for the intercept. However, instead of using the same distribution of b for all a, we use a conditional distribution

$$G(b|a_o; \hat{b}_{a_o}, b_L, b_U)$$

which is based on the <u>most likely</u> value of b, denoted $\hat{b}_{a_o}$, as that value of the slope of the straight line which connects the points a_o and $\hat{a} + \hat{b}\, M_{UB}$, i.e.

$$\hat{b}_{a_o} = \frac{\hat{a} + \hat{b}\, M_{UB} - a_o}{M_{UB}}$$

Bounds for b, given a_o, continue to be the bounds you provide. Thus, we assume the most likely value of b changes for different values of a but your level of knowledge, as described by the uncertainty bounds (b_L, b_U) remain the same for all a. Graphically, the relationship between a and b is shown in Figure 3.2.2a. The equation used for a given a_o is represented by the intermittent long-small dashed line (—— — ——) in Fig. 3.2.2a. The change here from the previous case, i.e. a, b independent, is that the most likely recurrence model changes for each value of a. It should be noted that, dependency on $\hat{a}$, $\hat{b}$, $(b_L, b_U,)$ and (a_L, a_U), occassionally produces

$$\hat{b}_{a_o} < b_L \quad \text{or} \quad \hat{b}_{a_o} > b_U$$

as shown in Fig. 3.2.2b and c. In this case, we impose the restrictions $b_{a_o} = b_L$ or $\hat{b}_{a_o} = b_U$ respectively.

An obvious question is "how much correlation does this procedure impose on a, b?". It will depend on the inputs, however, we have estimated the correlation using your response to Questionnaire 2. We find the correlation to range from close to -0.5 to close to -0.02. On the average, the correlation was about -0.22. Some specific illustrations are given in Table 3.2.1.

To summarize, the difference between treating a, b as independent and this case is, whereas in the former the most likely value of b is $\hat{b}$ your best estimate, the same for all a_o, in this case, the most likely value of b is $\hat{b}_{a_o}$ which changes with a_o. The bounds (b_L, b_U) remain the same in both cases. Thus with respect to your uncertainty in b, given a_o, this method implies that the range (b_L, b_U) remains the same for all a_o but the "peak"

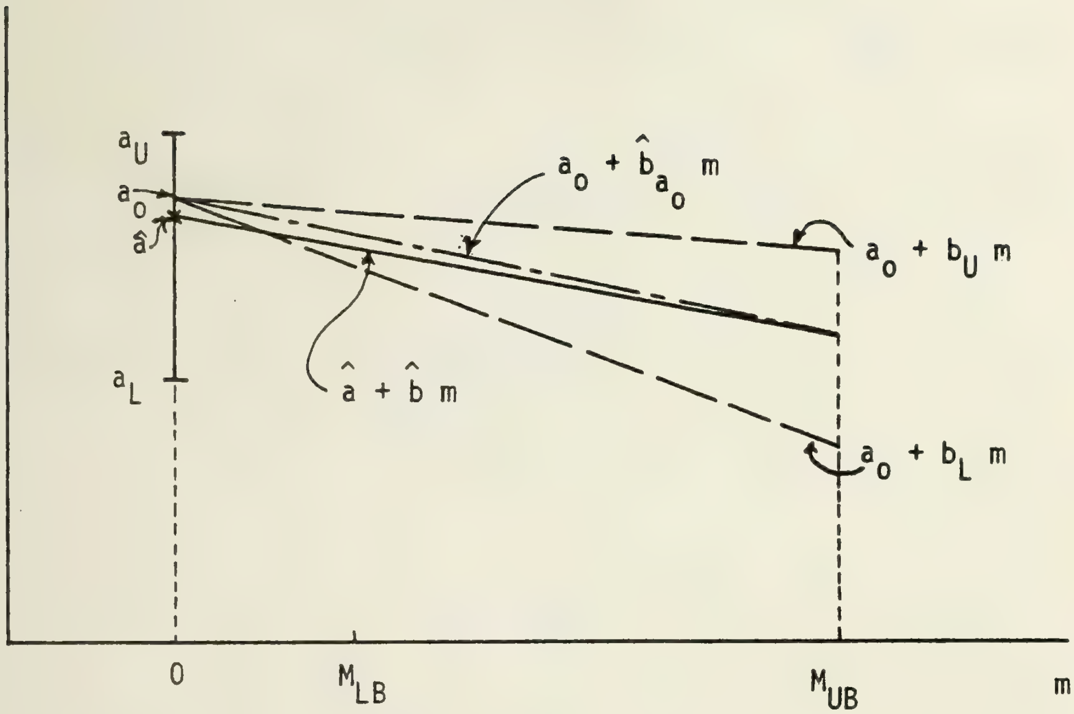


Figure 3.2.2a Bounding and Most Likely Recurrence Models When a and b are Treated as "Partially" Correlated

Fig. 3.2.2b

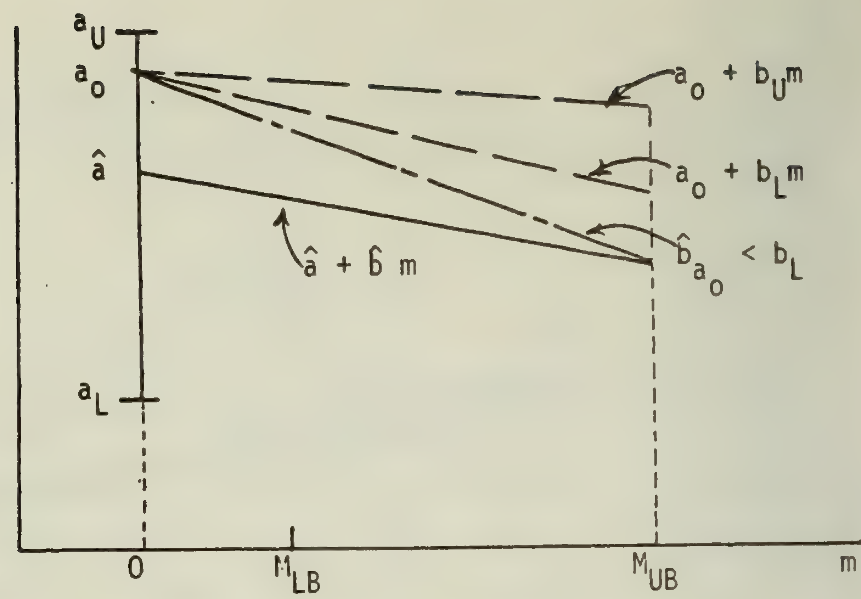


Fig. 3.2.2c

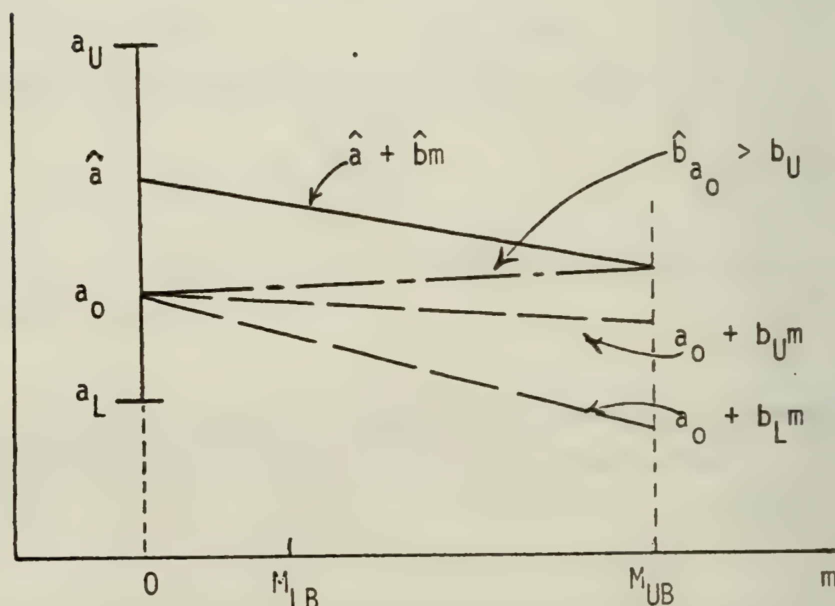


Figure 3.2.2 (Continued)

TABLE 3.2.1

Some Illustrations of Correlations Imposed by Treating
a, b as "Partially" Correlated

$(\hat{a}, \hat{b})$	(a_L, a_U)	(b_L, b_U)	M_{UB}	Correlation
2.434, -.906	2.344, 2.584	-1.170, -.906	4.5	-.037
1.5, -.59	1.4, 2.5	-.85, -.50	6.75	-.186
3.00, -.69	2.71, 3.26	-.74, -.64	8.7	-.245
4.167, -1.06	2.947, 5.387	-1.226, -.901	6.0	-.375
5.786, -1.40	4.786, 6.786	-1.50 -1.35	6.0	-.499

(region of the most probable value of the slope) of the uncertainty distribution changes with a_0.

3. <u>(a, b) are "highly" negatively correlated</u>

Alternative 2 introduced correlation in the estimates of (a, b) by making the most likely value of b depend on a but keeping the variation (b_L, b_U) the same for all a. Ideally, it seems like the most appropriate method would vary the range of b as well as the most likely value. This does not seem to be feasible given the information we derived from your response to Q2. To provide an alternative which introduces more correlation than alternative 2, we propose an alternative which reduces the variation in b, given a_0, to zero. That is, for each a_0 there is a unique value of b. The implication of this procedure is that the estimates of (a, b) are "highly" negatively correlated, in fact, the correlation is -1.0.

For this alternative the unique value of b, given a_0 is derived as follows:

o Given $\hat{a}$, (a_L, a_U), $\hat{b}$, (b_L, b_U) , there exists some $m^* > 0$ such that

$$a_U + b_L\, m^* = a_L + b_U\, m^*$$

which is,

$$m^* = \frac{a_U - a_L}{b_U - b_L}$$

o Given any a_0, the value of b_{a_0} is the slope of the line which connects a_0 to the point of intersection at m^*, i.e.

$$b_{a_0} = - \frac{(a_0 - a_L) - b_U\, m^*}{m^*}$$

It should be recognized that this procedure is only applicable if the best estimate model $\hat{a} + \hat{b}m$ also passes through the point of intersection at m^*. This will be guaranteed if the bounds (a_L, a_U) and (b_L, b_U) are symmetric about $\hat{a}$ and $\hat{b}$ respectively.

The basic concept of this alternative is that there is a unique slope for each intercept. Stated differently, the implication is that the uncertainty in the conditional value of b, given the intercept, is zero. Viewing this alternative from the standpoint of knowledge about log N_m, it suggests that one is most knowledgeable at certain values of magnitude. For example, consider the three cases illustrated in Figures 3.2.3a, b, c. In Figure 3.2.3a, clearly the implication is that the uncertainty in $\log_{10} N_m$ is less at M_{UB} than it is for M_{LB}. In Figure 3.2.3c the opposite is true. If m* lies between M_{LB} and M_{UB}, the implication is that the uncertainty is minimum for magnitudes between M_{LB} and M_{UB}.

3.3 Complementary Zone (CZ)

The purpose of this section is to help you in evaluating the parameters of the CZ. No action is requested from you. The seismicity parameters of the CZ determined from your answers to Questionnaire 2 exhibit a large amount of variation in the a and b values, as well as in the upper magnitude cutoffs. The following is an enumeration of some possible reasons for this fact:

- The surface areas of the CZ can be very different from one expert to the other.

- One expert may have constrained every seismogenic area to be part of a specific zone other than the CZ. In this case, the CZ clearly could have a low seismicity.

- Another expert may not have constrained all seismogenic areas to be part of a specific zone other than the CZ. This could be the case when the uncertainty on the location and seismicity parameters of some seismogenic areas is too large to warrant defining a specific seismic zone. In this case, some seismicity is allowed to "float" within the CZ, thereby leading to higher seismicity parameters for the CZ.

- There may have been some misunderstandings on the part of the experts as to the exact size, shape and location of the CZ.

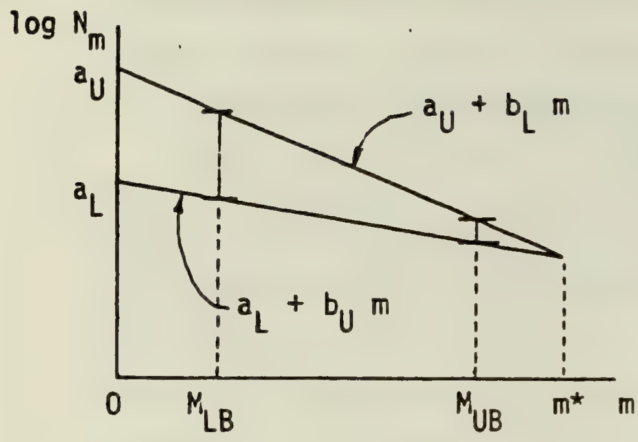


Figure 3.2.3a

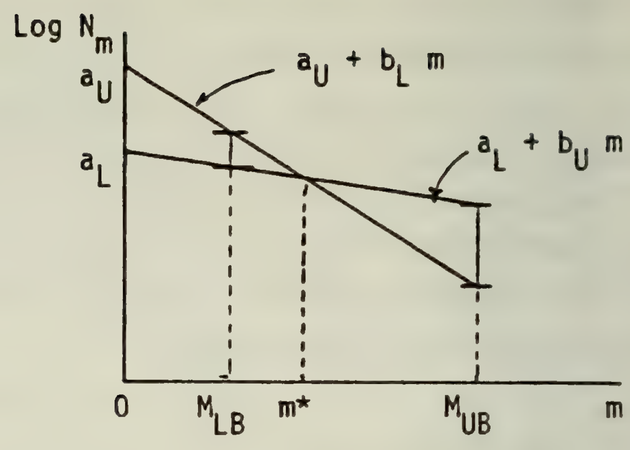


Figure 3.2.3b

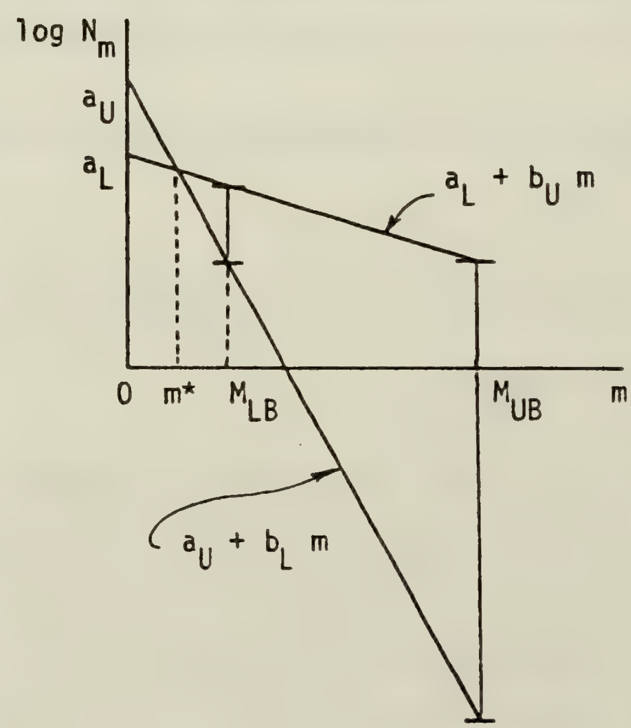


Figure 3.2.3c

Figure 3.2.3 Uncertainty Bounds for $\log_{10} N_m$ at M_{LB} and M_{UB} for Various m*

- o The experts may have lacked some knowledge as to the consequences of the choice of parameters of the CZ on the final hazard at the site.

- o And finally, as is the case for Expert 4 (see Table 3.3.1), the expert did not provide the seismicity parameters for the CZ, but only for a portion of it. In this case, LLNL extended these properties to the overall CZ.

In order to help you in defining the geographical boundaries of the CZ, a set of maps is provided in Figs. 3.3.1 through 3.3.11. In these maps the CZ is represented by the shaded area. In the case of Expert 4, zone 13 is shaded in one way and the zone identified as the CZ is shaded in a different way, but the actual CZ is the union of both these zones.

The seismicity parameters of the CZ's are presented for comparison in Table 3.3.1. One has to be careful in interpreting the values in Table 3.3.1 and translating them directly into a comparison in hazard values, as the characteristics of the CZ can be very different for the reasons mentioned above. Table 3.3.1 shows the map index of the CZ, the surface area as well as the a and b values, the upper magnitude cutoff, the number of earthquakes greater than magnitude 3.75 per year and unit of area for each expert.

The best estimate recurrence relationships are plotted in Fig. 3.3.12 from m = 3.75 to the upper magnitude cutoff M_U. These curves are expressed per unit area (10^6 km^2) and for 1 year. They can be used directly to make inferences on the relative hazard at sites located inside the CZ. For example, the CZ of Expert 10 has the highest density of earthquakes per unit area but has a relatively low magnitude cutoff (M_U), therefore one can infer that the hazard at low PGA will be the highest (for a site inside the CZ), but the hazard will decrease faster than for zones with higher magnitude cutoffs. On the other hand, a CZ with relatively low a and high M_U, such as in the case of Expert 2, will lead to relatively low hazard at low PGA values and relatively high values of the hazard at high PGA, thereby increasing the positive concavity of the hazard curve.

TABLE 3.3.1
AREA OF THE COMPLEMENTARY ZONE FOR EACH EXPERT

Expert Number	I.D. of Zone on maps	Area ($10^6 km^2$)	a	a per $10^6 km^2$	b Value	$N(M_o)/10^6 km^2$ for $m=m_o=3.75$	M_U
1	15	1.656	5.614	5.395	-1.48	.700	5.8
2	CZ	7.661	3.500	2.616	-1.00	.074	7.3
3	1	7.406	4.549	3.679	-1.10	.360	6.5
4(*)	CZ+13	5.785	2.590 & 2.150	1.962	-.90	.039	5.5
5	CZ	6.503	4.170	3.357	-.92	.810	(+)5.75
6	1	7.840	4.196	3.302	-1.04	.250	6.0
7	2	5.380	4.000	3.269	-.90	.780	6.7
10	19	7.904	4.890	3.992	-1.00	1.750	5.5
11	0/CZ	6.513	4.250	3.436	-.90	1.150	5.8
12	1	2.913	5.311	4.847	-1.28	1.110	5.0
13	CZ	9.310	4.600	3.631	-1.09	.350	6.3

Notes: (*) The entire complementary zone for Expert 4 is made of zone #13 and the zone named CZ on the map of Fig. 3.3.4. The areas are: 1.532 for zone 13 and 4.253 for the zone called CZ. The total is 5.785 as shown in this table for Expert 4. These two zones have the same seismicity parameters per unit of area.

(+) Expert 5 gave an upper MMI cutoff of 8 which is used in the relation MMI = 2m - 3.5 specified by the expert to obtain M_U = 5.75

Figure 3.3.1 Seismic Zonation Base Map for Expert 1

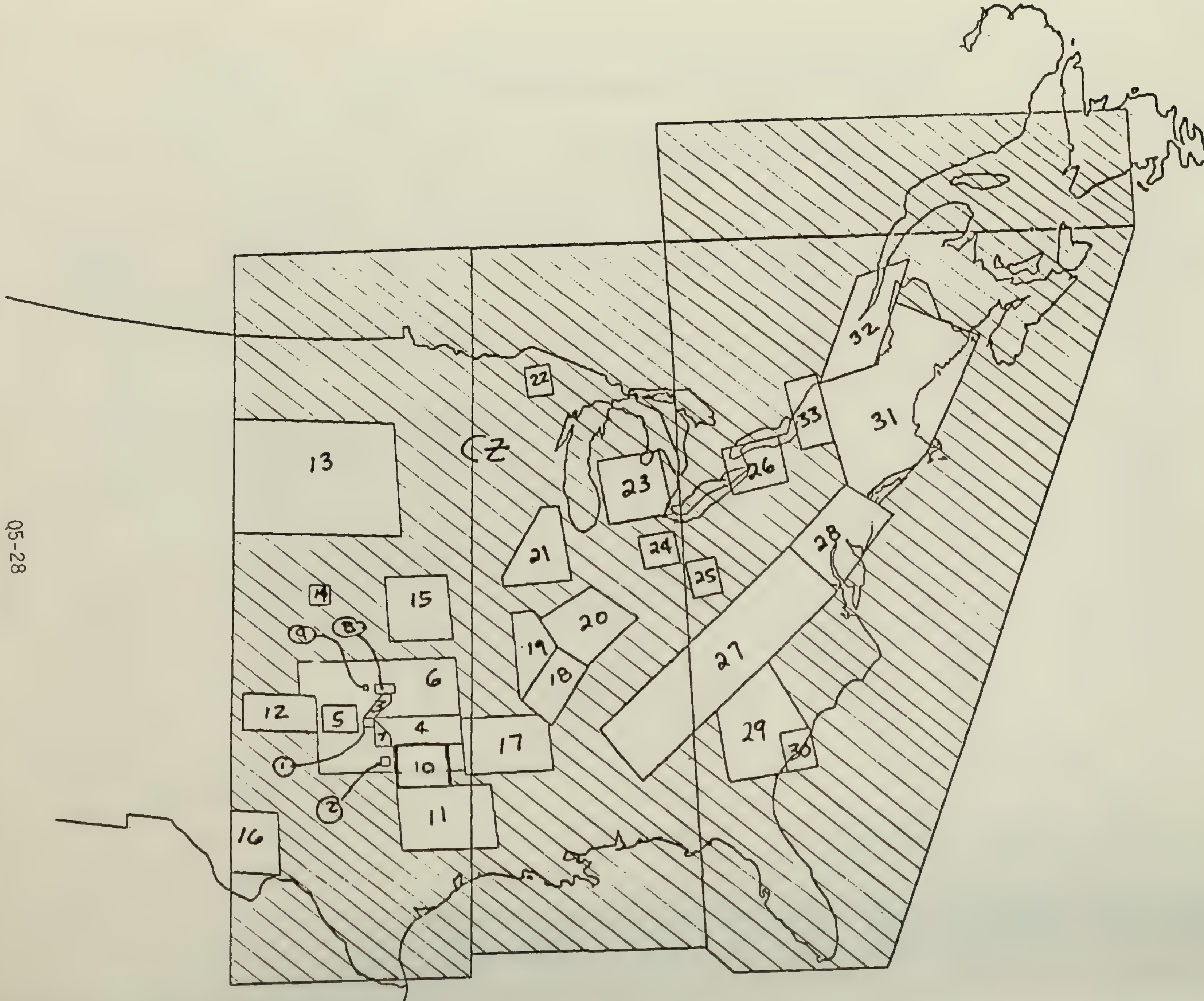


Figure 3.3.2 Seismic Zonation Base Map for Expert 2

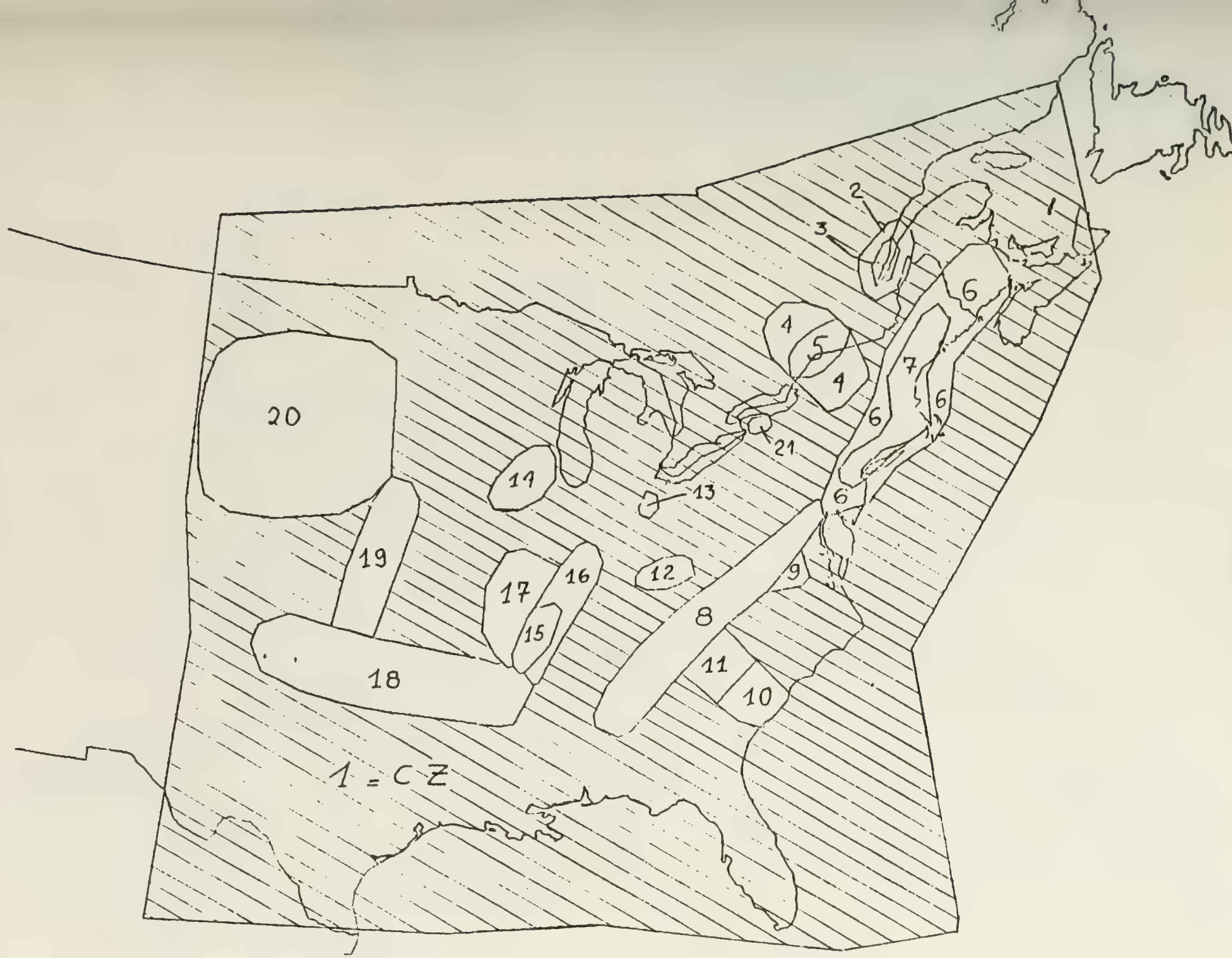
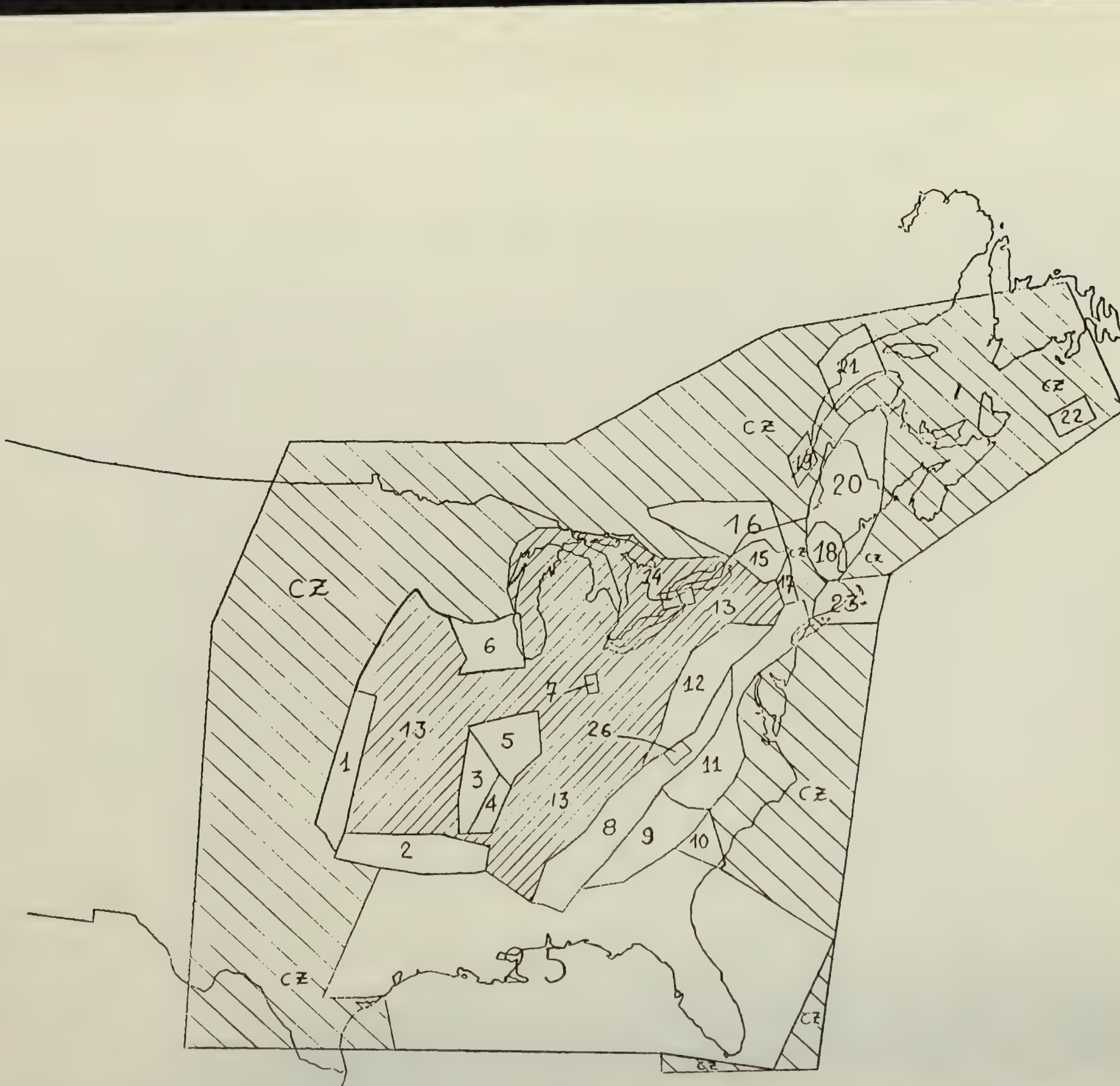


Figure 3.3.3 Seismic Zonation Base Map for Expert 3



Seismic Zonation Base Map for Expert 4

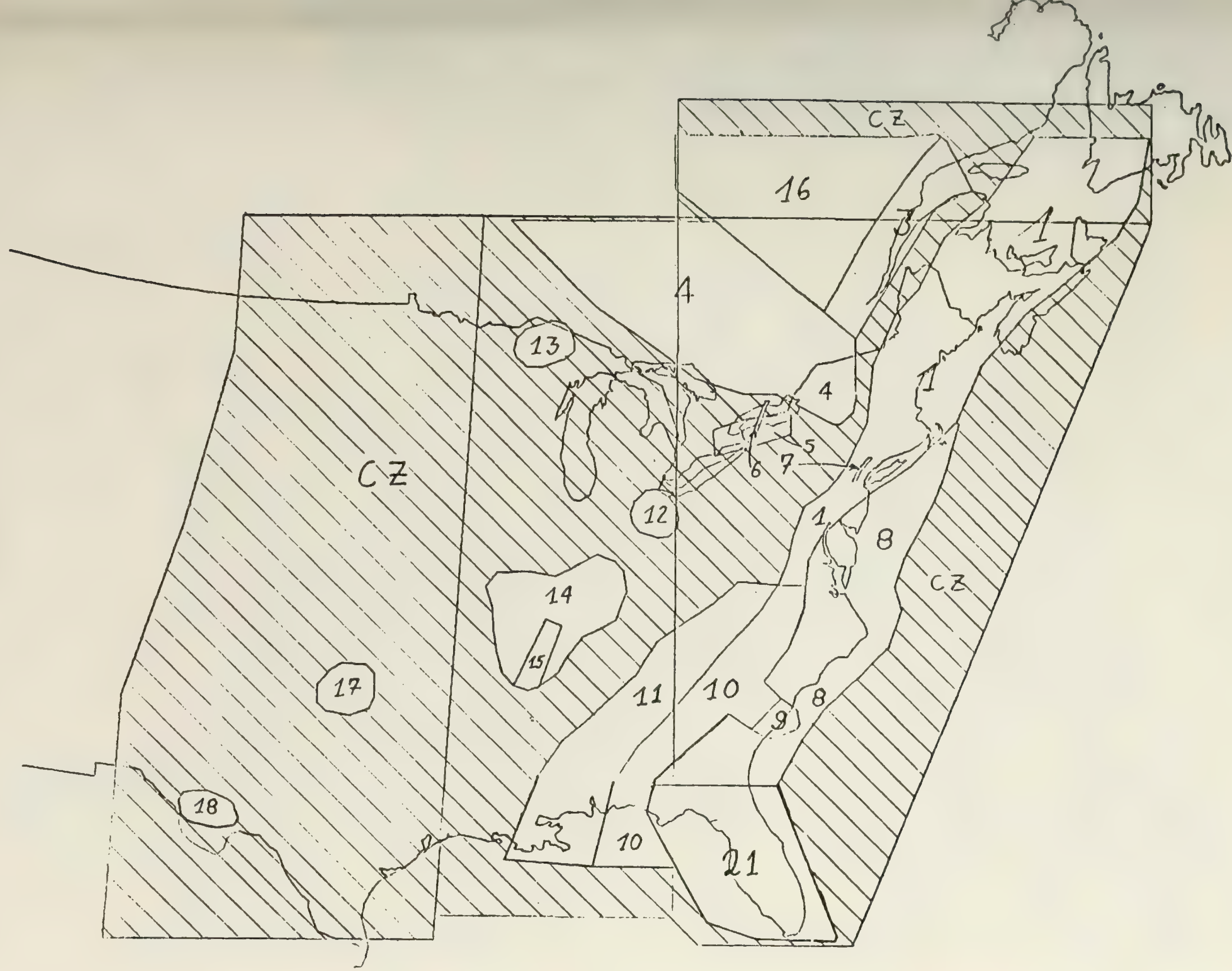


Figure 3.3.5 Seismic Zonation Base Map for Expert 5

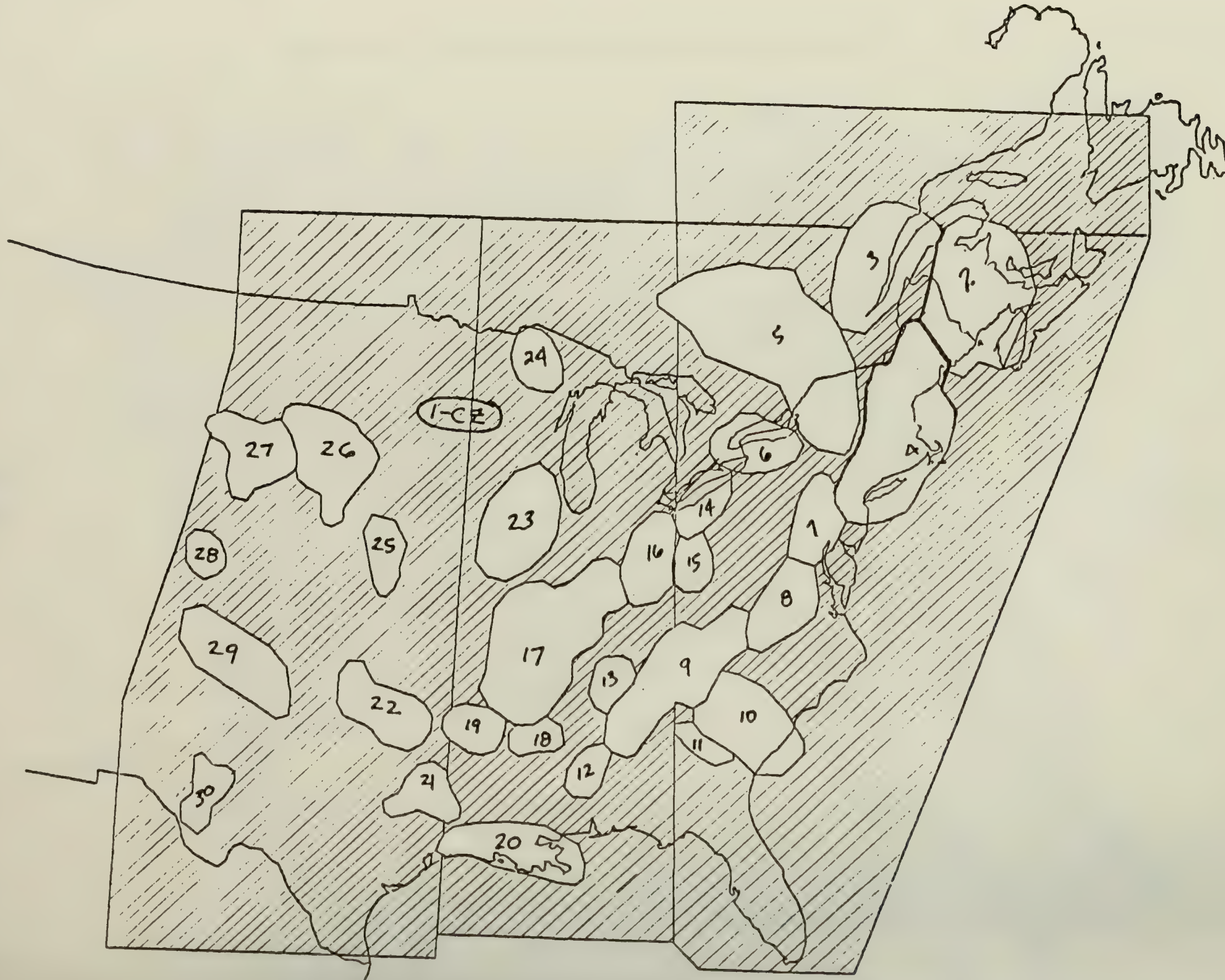


Figure 3.3.6 Seismic Zonation Base Map for Expert 6

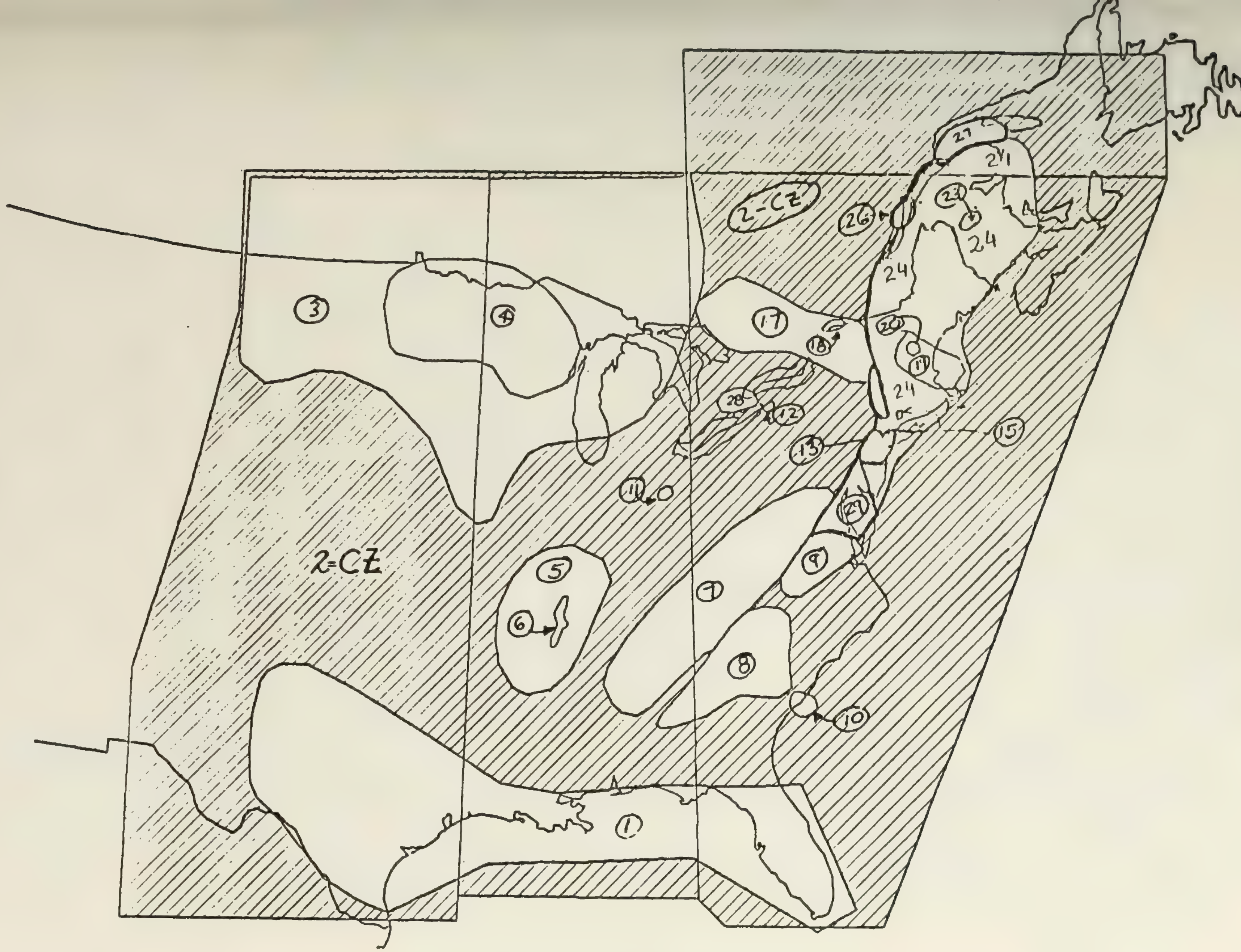


Figure 3.3.7 Seismic Zonation Base Map for Expert 7

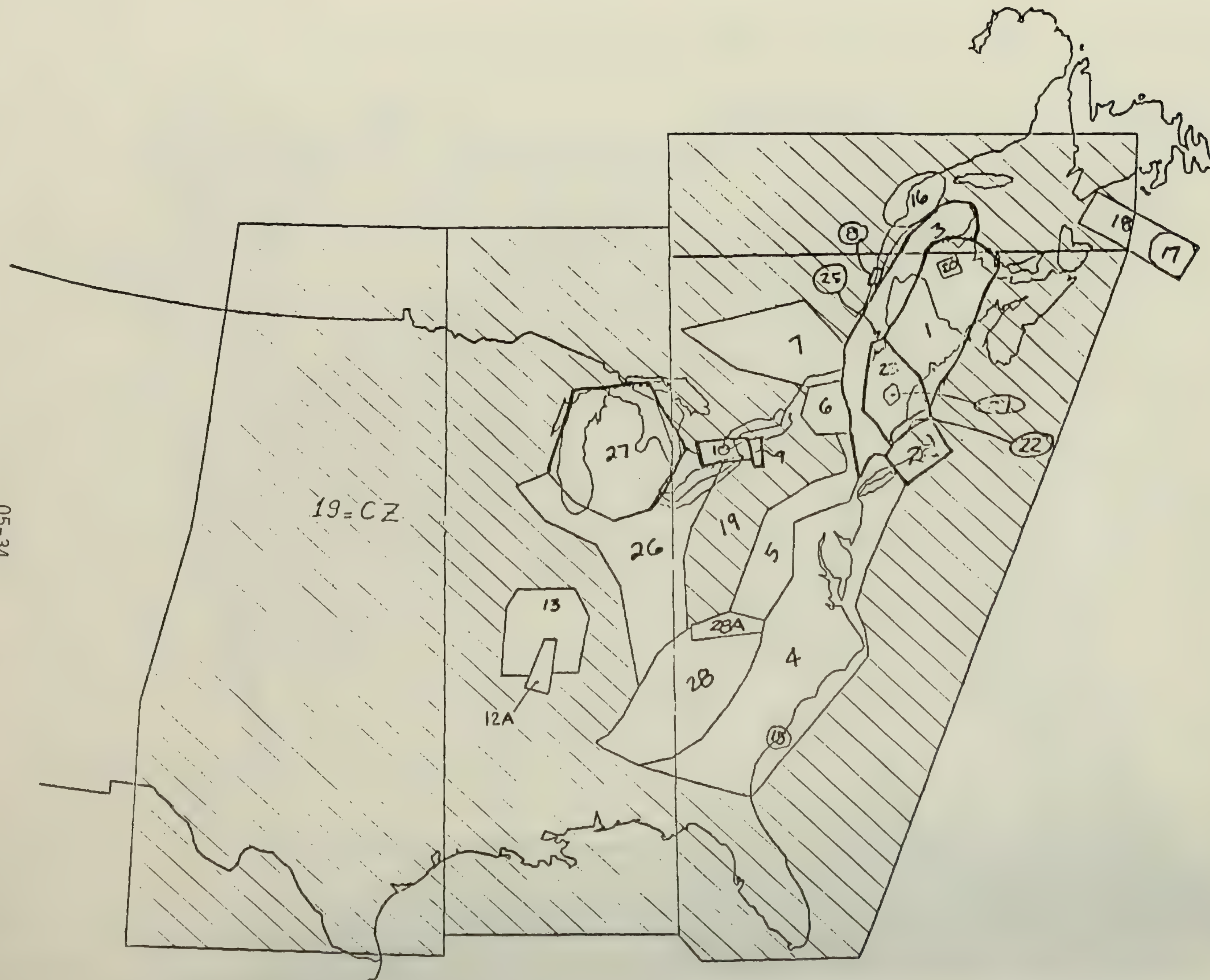
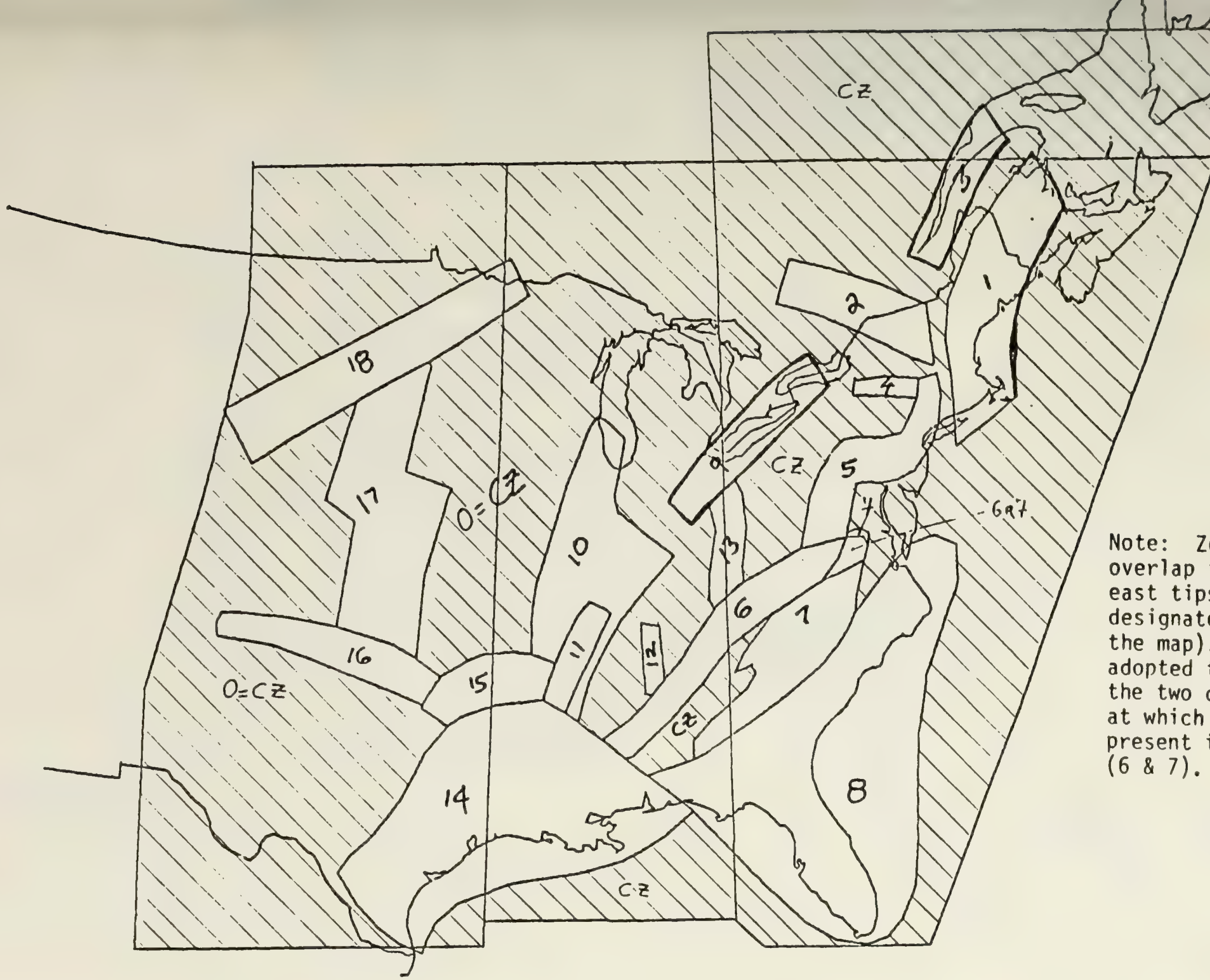


Figure 3.3.8 Seismic Zonation Base Map for Expert 10



Note: Zones 6 and 7 overlap in their northeast tips (subzone designated by 6 & 7 on the map). This model is adopted to acknowledge the two different depths at which seismicity is present in subzone (6 & 7).

Figure 3.3.9 Seismic Zonation Base Map for Expert 11

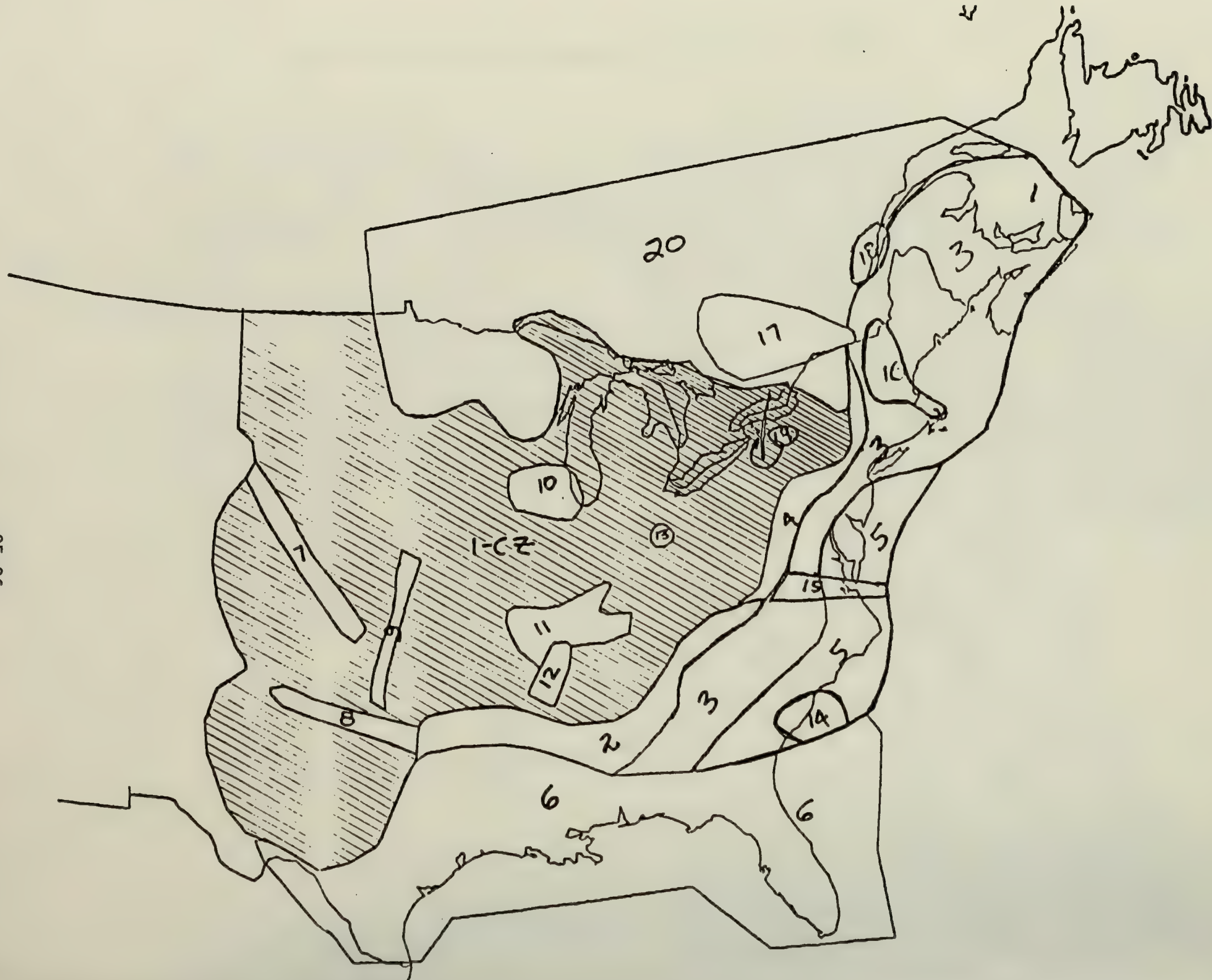


Figure 3.3.10 Seismic Zonation Base Map for Expert 12

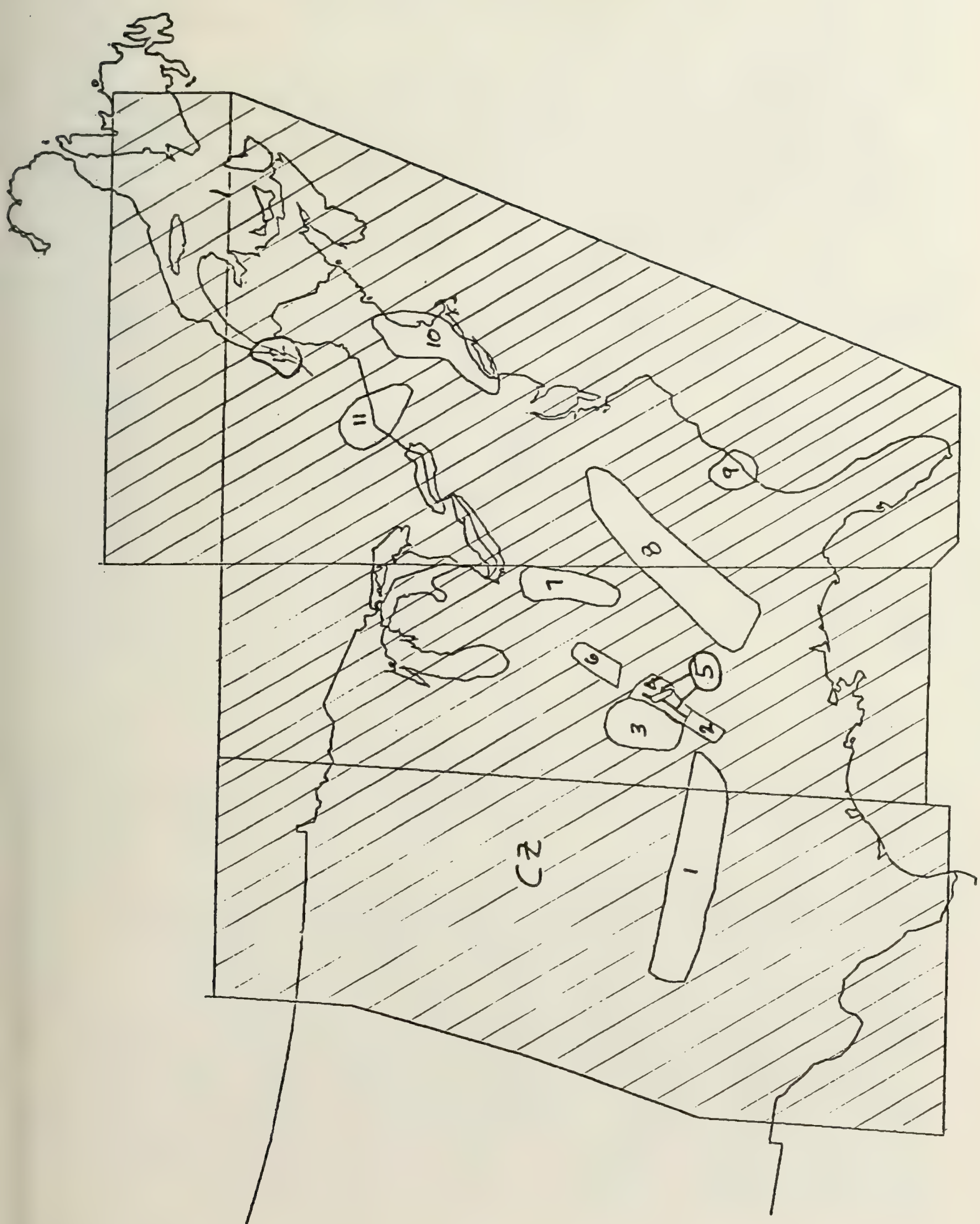


Figure 3.3.11 Seismic Zonation Base Map for Expert 13

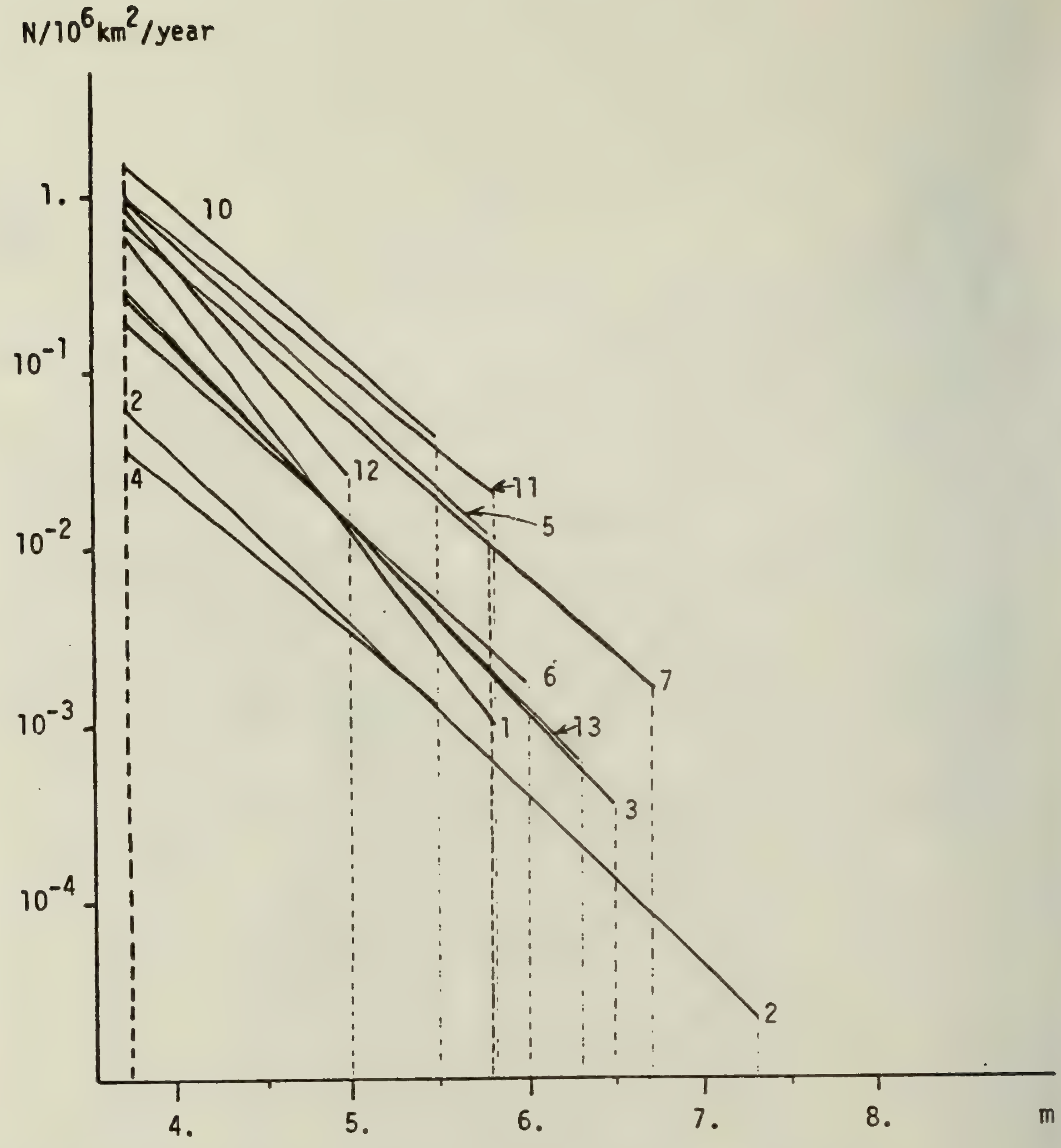


Figure 3.3.12 Number of earthquakes in the complementary zone (CZ), per year and normalized to a unit area of $10^6 km^2$, as a function of magnitude. Comparison between all the seismicity experts. The numbers refer to the experts' index used in the analysis. The interval of magnitude for which each of the lines is drawn is from the lowest magnitude used in the analysis ($m=m_0=3.75$) to the best estimate upper magnitude cutoff $\hat{M}_U$. For the purpose of this figure, the upper end of the curves (near $\hat{M}_U$) is not drawn exactly as they are actually used in the analysis. (See Section 3.1 for more details.)

Finally, you are invited to analyze the set of results presented to you at the December 1983 meeting to complete your understanding of the effect of the CZ on the hazard. In studying these results, you have to realize that a site which may be in the CZ for one expert may not be in the CZ for another expert.

4. <u>Completeness of the Catalogues of Earthquake and Aftershock Sequences</u>

The assessment of the parameters of the recurrence model is strongly dependent on the degree of completeness of the earthquake data available for a given zone. Furthermore, some catalogues of earthquakes contain aftershock sequences. A catalogue of earthquakes may be defined as complete over a time period of T years and for a range of magnitude $[m_1, m_2]$ or intensity $[I_1, I_2]$ if all the events with magnitude or intensity falling in these intervals form a sample representative of the long range seismicity of the area investigated. This implies that the necessary period of complete recording for frequent events (small events) is smaller than for less frequent and a fortiori for rare (large) events. On the other hand, as we consider events smaller and smaller in size, the likelihood of having them recorded in the catalogue decreases, whereas large and very large earthquakes are almost certain to have been recorded. This likelihood of recording depends principally on our ability to detect and properly assess a "size" (magnitude or source intensity) to the event.

As a consequence, the available catalogues for the EUS which include events as far back as the 17th century may be considered complete for rare events with return periods in the order of the time of recording, but they may not be considered complete for smaller events. The practical consequence of using an incomplete data set in the context of this analysis is the generation of an erroneous set of recurrence models. This analysis uses the form $\mathrm{Log}_{10}N_m = a + bm$ (or $\mathrm{Log}_{10}N_I = a-bI$ alternatively), where N is the number of earthquakes greater than m (or I) and a, b are parameters to be determined for each zone. Thus, using an incomplete data set would lead to low a values and low b values in comparison with the ones which would be obtained from a complete data set. There are several published methods to account for incompleteness, ranging from the ad hoc to more sophisticated statistical types.

An aftershock sequence in a data set may also lead to erroneous estimates of the recurrence laws and some analyst choose to remove the aftershock sequences from the catalogues of events.

In responding to Q2, the panel members were invited to use a catalogue of earthquakes of their choice. We have provided LLNL's catalogue to the experts who requested it. This catalogue has not been adjusted for completeness nor for aftershock sequences. Testing for completeness and removing aftershock sequences requires a high level of experience and judgment, thus it was left to each expert's discretion.

It is not appropriate for us to evaluate the methods you used to account for incompleteness and aftershocks. However, in order to formulate a generic evaluation of our analysis, we feel it necessary to survey your level of effort in handling incompleteness and aftershocks.

Thus, in Questions 4.1 to 4.3 you are requested to indicate what was your level of effort in dealing with the problem of completeness (Question 4.1) of the catalogue you used and the problem of aftershock sequences (Question 4.2) either generically for all EUS or specifically zone by zone. Question 4.3 gives you an opportunity to elaborate on the methods used.

5. Self Weights

During the feedback meeting it became clear that your self-ratings (Responses to Q3) were not all on the same basis. Your comments suggested that some of you rated yourself relative to the other panel members whereas others rated yourselves relative to some overall knowledge of zonation and seismicity for the EUS. Therefore, it is appropriate that we establish a basis for you to rate yourself and then give you the opportunity to reconsider your self-ratings.

Although there are several bases that one might consider for forming self ratings, three that we consider appropriate are:

o Your level of expertise relative to the other panel members.

- o Your level of expertise relative to the scientific community at large.

- o Your level of expertise relative to an "absolute level" of overall knowledge.

There is no general agreement on which is the preferred basis to use, however, two points influence our consideration.

- o The ratings are used to establish weights to use in combining hazard results and uncertainties. The combinations are based on a relative weighted averaging process.

- o Development of the weights was based on treating your self ratings as a measure of your "utility" of your estimates of the hazard.

The former point suggests that the "level" or basis is not important, thus, it is not important what basis one uses to measure ones level of expertise. However, the latter point suggests that the ratings should reflect some measure of overall worth of ones estimates.

After some consideration we have decided to ask you to use the scientific community at large as the basis for self rating your level of expertise. Although this request may not be as easy as rating yourself relative to the other panel members, we believe the overall study will benefit from your assessment of your level of expertise relative to the overall scientific community. In particular, the overall ratings of all panel members will give us some indication of how you rate yourself (as a panel) relative to other groups of experts who might have been assembled.

6. Questions

Section 2: Zonation Maps

Question 2.1

Please review the zonation maps that you provided in answer to Q1 and generate updated versions of these maps if you think it is necessary.

You will find the original maps that you designed in response to Q1 which you can use to respond to this question if your modifications are not extensive. Please indicate your modifications by altering these same maps clearly (using different colors and a clear key, for example). Feel free, however, to use a new blank map sheet if your modifications are extensive or if you have new alternatives. In any case, please return the original maps together with your responses to this questionnaire.

Question 2.2

Please update Table A1 as necessary.

Question 2.3

Please update Table A2 as necessary.

Section 3: Seismicity

Question 3.1

Please indicate the magnitude recurrence model we should use to develop hazard curves based on your opinions about seismicity.

_____ LLNL Model

_____ Truncated Exponential Model

Question 3.2

Please indicate the most appropriate way for us to handle correlation between your estimate of the intercept, a, and slope, b, of the magnitude recurrence equation.

_____ (a, b) should be treated "independently"

_____ (a, b) should be treated as "partially" negatively correlated

_____ (a, b) should be treated as "highly" negatively correlated

Question 3.3

Please review the seismicity estimates you provided in response to Q2 and make any modifications you deem appropriate. In doing this, please keep in mind any changes that are necessary due to changes in zonation (i.e. responses to Questions 2.1-2.3) and your responses to how we should treat the magnitude recurrence modeling (Question 3.1) and correlation between (a, b) (Question 3.2).

Tables, as provided in Q2, are included. You need not recopy any information which is the same as before. Only fill in the appropriate modifications.

Section 4: Completeness of the Catalogue and Aftershock Sequences

Question 4.1

What level of consideration would you say you gave to the problem of completeness of the catalogue you used in your final answers about seismicity in Section 3 of this Questionnaire? Please respond by filling Table 4.1 with check marks ( ) in columns 2 to 5. You may chose to answer specifically for each zone or have a single generic answer. In Table 4.1, the zone index numbers refer to the zone numbers on your final zonation maps, which you might have updated in response to question 2.1 of this Questionnaire.

Question 4.2

What level of consideration would you say gave to the problem of aftershock sequences in the catalogue you used in your response about your final answers on seismicity in Q2 and Section 3 of this Questionnaire?

Please respond by filling Table 4.1 with check marks ( ) in columns 6 to 9.

Question 4.3 (Response to this question is optional.)

If you deem it appropriate, please elaborate on the method you used to account for incompleteness in the catalogue you used and/or to account for aftershock sequences.

Section 5: Self Rating

Question 5.1

For each of the four regions identified below, please indicate your level of expertise (on a scale of 1-10, with 1 indicating a low level of expertise) with regard to the geologic, tectonic, and seismic characteristics within the region.

	REGION	SELF-RATING
I	Northeast	______
II	Northcentral	______
III	Southeast	______
IV	Southcentral	______

Table A1
Level of Confidence in Existence of Zones

Zone Index on Final Updated Maps	Level of Confidence in Existence	If Zone does not Exist, it Becomes Part of Zone Number	Additional Comments
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			
17			
18			
19			
20			
21			
22			
23			

Table A1 (Continued)
Level of Confidence in Existence of Zones

Zone Index on Final Updated Maps	Level of Confidence in Existence	If Zone does not Exist, it Becomes Part of Zone Number	Additional Comments
24			
25			
26			
27			
28			
29			
30			
31			
32			
33			
34			
35			
36			
37			
38			
39			
40			
41			
42			
43			
44			

Table A1 (Continued)
Level of Confidence in Existence of Zones

Zone Index on Final Updated Maps	Level of Confidence in Existence	If Zone does not Exist, it Becomes Part of Zone Number	Additional Comments
45			
46			
47			
48			
49			
50			

Table A2
Level of Confidence in Boundary Shapes of
Zones or Cluster of Zones and Alternative Shapes

Zone Number(s) of the Zones or (Cluster of Zones) in Final Updated Map	Level of Confidence in Boundary Shape	Zone Index of Alternative Zone (or Cluster of Zones) Boundary Shape	Additional Comments

MAGNITUDE DISTRIBUTION

Question	Q3-8	Q3-9	Q3-10	Q3-11	Q3-12	Q3-13		Q3-14		Q3-15	Q3-16	Q3-17	Q3-18		Q3-19	
	MAGNITUDE-RECURRENCE RELATION											PROBABILITY DISTRIBUTION (5)				
			Magnitude-Recurrence Curve					Model Range		Extrapolation				Parameters of Distribution		
Zone (1)	Mag. Scale	Sat. Value (2)	Model	Coef. Best Estimate	Time Length	Coef. Conf. Bounds Lower	Upper	Lower M_{LB}	Upper M_{UB}	Between M_o, M_{LB}	Between M_{UB}, M_{UU}	Magnitude Scale	Probability Distribution	Best Estimate	Confidence Bds. Lower	Upper

(1) Please use the index numbers identifying the zones on your maps of the zonation of the EUS.
(2) Indicate a saturation value only if constrained by that value in your responses.
(5) Respond to Questions 3-17 through 3-19 only if you did not respond to Questions 3-8 through 3-16.

Update of Seismicity Parameters Response to Question 3.3

Table 4.1
Level of Consideration on Completeness and Aftershock Sequences

Zone Number	Completeness				Aftershock Sequences				Additional
on Updated Map	None	Low	Medium	Full Analysis	None	Low	Medium	Full Analysis	Comments
1	2	3	4	5	6	7	8	9	10
For All Zones If you answer Generically									
1									
2									
3									
4									
5									
6									
7									
8									
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SIXTH QUESTIONNAIRE - FEEDBACK QUESTIONNAIRE ON GROUND MOTION MODELS (Q6)

1.INTRODUCTION

The purpose of the feedback meeting is to give the members of the Ground Motion Panel (GMP), a chance to update their input of the ground motion models, and to express their opinion on the methodology to be used in accounting for local site effects. Hence, as a member of the GMP, this meeting was intended to give you:

1) An understanding of how we interpreted and used your input.

2) A chance to review the implications of your input, i.e., the combination of ground motion models with the seismicity models provided by the Seismicity Panel.

3) A chance to either correct any misinterpretations we (LLNL) might have made or alter your responses in light of the results and or responses from other panel members.

4) A chance to evaluate the proposed methods to correct for local site soil conditions by assigning a level of confidence to each one of them, and possibly propose modifications or different methods.

5) A chance to revise your weights relative to other responses.

To assist you in reviewing and updating your input, we have sent each of you a copy of our Interim Report. At the June 27, 1984 meeting, we briefly reviewed our methodology (which is discussed in detail in Section 2, and Appendix D of the Interim Report) and gave you an opportunity to ask questions. Section 3.4 of the Interim Report gives our interpretation of the input you provided in response to the Ground Motion Questionnaire given in Appendix C.

In addition, this document provides you with additional information. In particular, Section 2 of this document provides a more complete listing of the models and the weights for each model than given in the Interim Report and includes the responses from Expert 2 which were not available at the time the Interim Report was published. Section 3 of this document expands upon the results presented in Sections 4.1 and 4.2 of the Interim Report with emphasis on ground motion models and their contribution to the uncertainty of the estimate of the seismic hazard at selected sites. The results presented in Section 3 of this document have been updated to include the input from Ground Motion Expert 2.

In Section 4 of this document we briefly revisit ground motion saturation and other topics. In Section 5 we address the approach we propose using to correct for the local soil conditions. In keeping with our Monte Carlo approach, several alternative schemes are proposed which you will be asked to evaluate by providing a level of confidence for each one of them. Section 6 contains the ground motion feedback questionnaire.

2. REVIEW OF THE GROUND MOTION MODELS SELECTED BY THE PANEL EXPERTS

2.1 Background

The ground motion models presented in this section are the ones selected by the GMP experts in response to questionnaire Q4. In Q4, we (LLNL) organized all possible availale models into several classes, described their origins, characteristics and limitations. You were then requested to choose one model in each class and to assign a level of confidence to each of the classes.

However, the enumeration of models provided in this section contains some models not mentioned in the questionnaire Q4, and is also more complete than the list provided in Table 3.4.3 of the Interim Report. The reasons for this are as follows:

1. The list of possible models provided in the questionnaire Q4 was not as complete as possible and two models have been added by one expert, prior to making the computations reported in the Interim Report. These two models include the acceleration model number 27 and the spectra model number 119 of Table 3.4.3 in the Interim Report, which are both labeled "Trifunac-Anderson."

2. One expert who had not been able to provide his answers to Q4 in time for performing the analyses reported in the Interim Report, returned his answer recently permitting us to include it in this section. However, the effect of this new input requires some more analysis to determine the impact of these new models on the hazard. This is treated in Section 3.

For the large part, all the models (except for 3 models) presented in this section were described in detail in the questionnaire Q4, which you all have, (it is also the Appendix C of the Interim Report), and this will not be repeated here. In this section, we present the models by classes and give a short description and reference for the models not present in Q4. We also present the method of simulation used in the calculations for the random

selection of ground motion models and give, for each expert, the levels of confidence assigned to each class of models.

2.2 The Ground Motion Models

2.2.1 Acceleration models.

There are seven classes of acceleration models. Five of them are intensity based, and two are direct. Table 2.1 gives the list of PGA attenuation models arranged by classes. It also gives for each model a file index number which cross references it with Appendix A. The Appendix A is a listing of the actual coefficients of each model as used in the analysis. The index number is not the same as the index of Table 3.4.3 of the Interim Report for velocity and spectra models as a result of addition of new models. Table 2.1 also contains an indicator which tells us if the models distinguish between soil or rock. In the last four columns, Table 2.1 provides the index of the expert who chose the model as a best estimate model for each region. The geographical definition of the regions is given in Fig. 2.1.The model number 27, labeled "Trifunac-Anderson," was obtained by using the Gupta-Nuttli (Central U.S.) intensity attenuation relationship with the Trifunac (1976) (G16) acceleration versus Site intensity relationship. The equation A3 of questionnaire Q4 is different from the Gupta-Nuttli relationship, only in its leading coefficient of 3.2 instead of 3.7. This "modified Gupta-Nuttli" equation was developed in the S.E.P. study in an arbitrary fashion by decreasing the intensity of a half unit to account for the fact that the relationship was based on isoseismal data rather than individual intensity reports. If we were to call A6 the Gupta-Nuttli equation, the Trifunac-Anderson relationship used for the interim report would be labeled A6-G16. This relation was updated as a result of the feedback meeting of June 27. The final equation will use "Modified Gupta-Nuttli" equation A3. (thus, it becomes A3-G16.), and to make it consistent with the other models it uses the coefficients for soil (S=0) instead of rock (S=2). This last update applies also to spectral model#125.

The value of γ used in the Campbell's (1982) equation (e.g. D13) is 0.002, and the Nuttli equation (D21) was obtained by using the h_{min} value given in Nuttli's letter of January 24, 1983 (see Appendix C of Interim Report). Furthermore, it has to be stressed that the hazard calculation assumed all distances to be epicentral distances. Because of this limitation the experts have been requested to factor this in their evaluation of the models, and it is reflected in the attribution of levels of confidence provided to us (LLNL) as responses to questionnaire Q4. These models are plotted for each class, for magnitude m_b = 5 and 7, in Figure 2.2 through 2.7. Note that model number 27 has been updated and actually becomes model number 12. Furthermore, a new model has been proposed for your consideration, at the June 27 meeting.

This model developed by G. Atkinson, is described in detail in Section 7 of this document, which is a copy of the paper submitted by the author for publication in BSSA; and appended here with her permission. This model has been added in the list of models to choose from in Section 6. Because of the way it was developed, it falls in the category of direct models and is labelled D22 in Table 6.1.

2.2.2 Velocity Models

As for acceleration, there are seven classes of peak ground velocity models, which are given in Table 2.2. The same general remarks made for acceleration applies to velocity. In addition, note that expert number 5 did not provide a velocity model, and expert number 2 provided a model not described in questionnaire Q4. This is the model GV53 developed by Klimkiewicz G, G and Pulli, JP 1983, which can be found in Earthquake notes, V54, N.1, p. 10. These models are plotted for each class, for magnitude m_b = 5 and 7, in Figure 2.8 through 2.12.

2.2.3 Spectra Models

The spectra models were separated into six classes. The first three classes consist of scaling spectra shapes, namely the Reg. Guide 1.60, the NBS, 1978-ATC and the Newmark-Hall spectral shapes. Reg. 1.60 and ATC shapes are anchored with one acceleration equation and Newmark-Hall are anchored with both acceleration and a velocity equation. The next three models are intensity based and were obtained by using distance weighting, magnitude weighting and no weighting. The no-weighting intensity based model was taken from Trifunac and Anderson's report "Preliminary Empirical Models for Scaling Absolute Acceleration Spectra," Report No. CE 77-03, USC, 1977. In all cases, the spectra used in the analysis assume a 5% damping.

Table 2.3 lists the spectra models, and Figure 2.13 through 2.16 shows these spectra plotted for the rock site conditions and for m_b magnitudes 5 and 7 for distances of 10 and 100 km.

2.2.4 Best Estimate Models

Figure 2.17 shows the best estimate (BE) acceleration ground motion models, Fig. 2.18 through BE velocity models and Figs. 2.19a and b shows the BE spectra models selected by the GMP members for magnitudes 5 and 7 and for distances 10 and 100 km. Tables 2.1 - 2.3 indicate which expert selected the various models and for which regions the models are assumed to be BE models.

2.3 Random Uncertainty

The values of the standard deviation on the logarithm of the ground motion parameter used in the analysis are presented in Table 2.A. In most cases these values are identical to the ones provided by the experts as answers to questionnaire Q4. However, it was necessary to make some interpretation in some cases. For instance, one expert provided a different standard deviation for each frequency. We need only one value obtained by averaging the g values given by the expert, after discussing the problem with him.

2.4 Model Uncertainty

The hazard analysis accounts for the model uncertainty by assuming a given distribution of ground motion models. The actual calculations are performed by using a Monte Carlo simulation technique where the hazard is calculated for each sample ground motion model. The models are drawn from the discrete probability distribution of models constructed with the input from questionnaire Q4. The probability of each model being the right one, for a given expert, is assumed proportional to his level of confidence in the class to which that model belongs. The Table 2.5 gives the cumulative levels of confidence assigned to each ground motion model by each expert to the models they selected. The actual discrete probability distribution of the ground motion models used in the analysis is simply a scaled version of the cumulative values presented in Table 2.5 a, b and c. The scaling value is 1/5 = .2. In addition, however, the hazard analysis accounts for the self rates you provided in questionnaire Q4.

TABLE 2.1

List of Peak Ground Acceleration Models
(Names of models refer to the Classification in
Questionnaire Q4 - or Interim Report, Appendix C, Section 7),
and the regions are shown on the map of Figure 2.1.

Class of Model	Model Name	Index in file of Appendix A	Distinguish Rock - Soil	Expert for whom it is a best estimate model (per region) Region NE	SE	NC	SC
	A1-G16	8	No				
1	A3-G15	1	No				
(Intensity-	A3-G16	12	Yes				
no weighting)	A4-G12	4	No				
	A4-G16	16	Yes				
	A5-G16	20	Yes				
	A6-G16	27	Yes	5	5	5	5
	A1-G21	9	No				
2	A1-G22	30	Yes				
(Intensity -	A3-G21	13	No				
Distance	A3-G22	32	Yes				
Weighting)	A4-G21	17	No				
	A4-G22	31	Yes				
	A5-G21	21	No				
	A5-G22	29	Yes				
	A1-G31	10	No				
3	A3-G31	3	No				
(Intensity-	A4-G31	18	No				
Magnitude	A5-G31	22	No				
Weighting)							

TABLE 2.1 (Continued)

Class of Model	Model Name	Index in file of Appendix A	Distinguish Rock - Soil	Expert for whom it is a best estimate model (per region) Region NE	SE	NC	SC
	A1-G41	11	No				
4	A3-G41	15	No				
(Intensity -	A4-G41	19	No				
Magnitude	A5-G41	23	No				
& Dist.							
Weighting)							
	G51	28	No			2	
5	G52	24	No		2		2
(Semi-	G53	5	No	2			
emperical)							
	D12	6	No				
6	D13	25	No	3	3	3	3
(Direct-1)	D14	26	No				
7	D21	7	No	1,4	1,4	1,4	1,4
(Direct-2)							

TABLE 2.2

List of Peak Ground Velocity Models
(Names of models refer to the Classification in Questionnaire Q4 -
or Interim Report, Appendix C, Section 7), and
the regions are shown on the map of Figure 2.1)

Class of Model	Model Name	Index in file of Appendix A	Distinguish Rock - Soil	Expert for whom it is a best estimate model (per region) Region NE	SE	NC	SC
1	A1-GV12	38	Yes				
ensity	A3-GV12	33	Yes				
eighting)	A4-GV12	44	Yes				
	A5-GV12	47	Yes				
2	A1-GV22	39	Yes				
ensity	A3=GV21	34	No				
.	A3-GV22	42	Yes				
hting)	A4-GV22	45	Yes				
	A5-GV22	48	Yes				
3	A1-GV31	40	No				
ensity	A3-GV31	35	No				
	A4-GV31	46	No				
hting.	A5-GV31	49	No				
4	No models						
ensity-							
& Dist.							
hting)							
5	GV51	50	No			2	
i-	GV52	36	No		2		2
irical)	GV53	52	No	2			
6	DV12	51	No				
ect-1)							
7	DV21	37	No	1,3,4	1,3,4	1,3,4	1,3,4
ect-2)							

TABLE 2.3

List of Pseudo Velocity Spectra Models
(Names of models refer to the classification in Questionnaire Q4, and
Interim Report, Appendix C, Section 7.
The regions are shown on the map of Figure 2.1

Class of Model	Anchor equation Acceleration and/or Velocity	Index in file of Appendix A	Distinguish Rock - Soil	Expert for whom it is a best estimate model (per region) Region NE	SE	NC	SC
RS1	G51	161	No				
(RG 1.60)	G52	170	No		2		2
	G53	179	No				
	D13	80	No				
	D21	71	No				
RS2	G51	134	No			2	
(NBS, 1978	G52	143	No				
ATC	G53	152	No	2			
	D13	98	No				
	D21	89	No				
RS3	G51/GV51	188	No				
(Newmark	G52/GV52	197	No				
Hall)	G53/GV53	206	No				
	D13/DV21	116	No	3	3	3	3
	D221/DV21	107	No	1,4	1,4	1,4	1,4
RS4 (Dist. Weight)	SEP 1 Bernreuter	53	No				
RS5 (Mag-weighted)	SEP 2 Bernreuter	62	No				
RS6 (No weighting)	Trifunac-Anderson	125	Yes	5	5	5	5

TABLE 2.4

Random Uncertainty Input
Values of "sigma" used in the analyses[1]

Expert Index		Acceleration Region NE	SE	NC	SC	Velocity Region NE	SE	NC	SC	Spectra Region NE	SE	NC	SC
1	Low	.35				.40				.45			
	Best	.5				.55				.60			
	Up	.65				.70				.75			
2	Low	.4				.3				.4			
	Best	.6				.5				.6			
	Up	.8				.7				.8			
3	Low	.48				.64				.53			
	Best	.6				.76				.65			
	Up	.72				.88				.77			
4	Low	.5	.5	.5	.5	.5	.5	.5	.5	.7			
	Best	.6	.6	.55	.6	.6	.6	.55	.6	.9			
	Up	.8	.8	.7	.8	.8	.8	.7	.8	1.4			
5[2]	Low	.6								.6			
	Best	.6								.6			
	Up	.6								.6			

Notes: 1. Values of signma not given for SE, NC, and SC are identical to those of NE.
2. Expert 5 did not provide values for velocity.

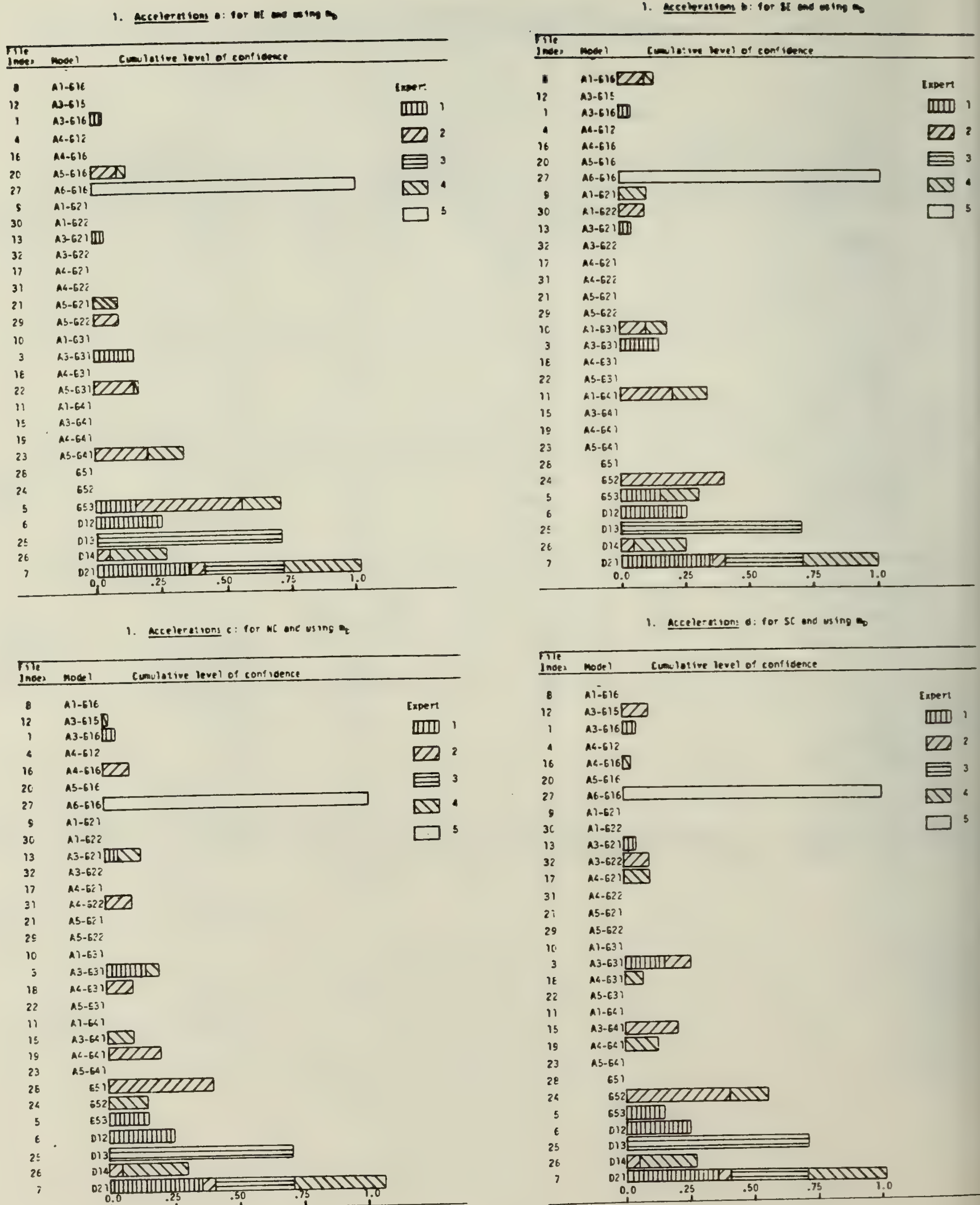
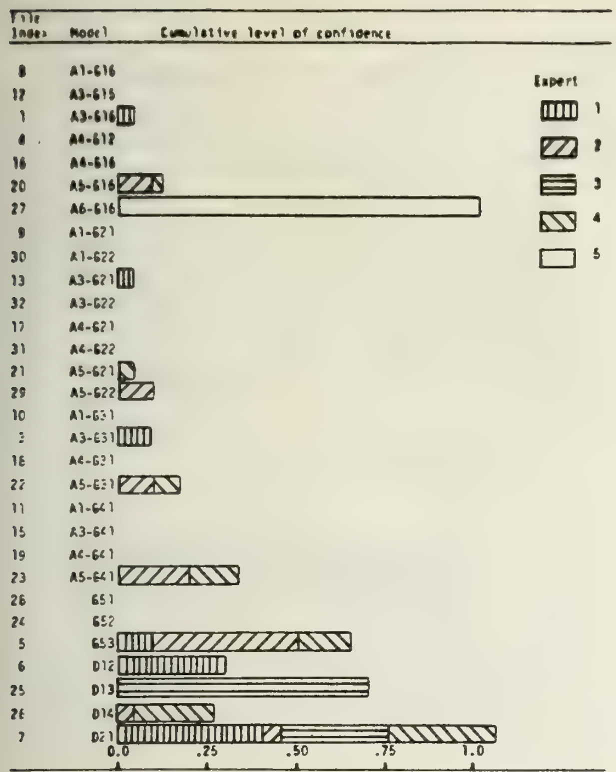
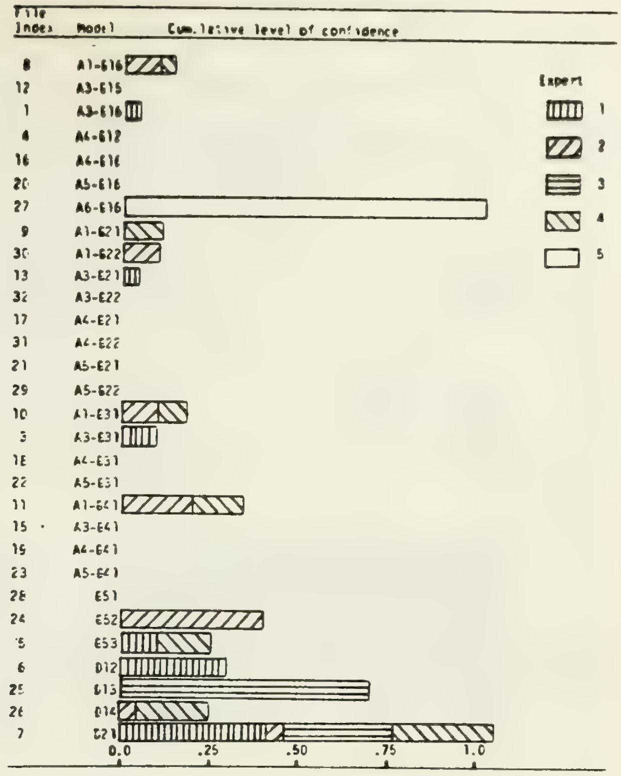


Table 2.5 Cumulative values of the levels of confidence assigned to the models in the analysis, for acceleration and spectra.

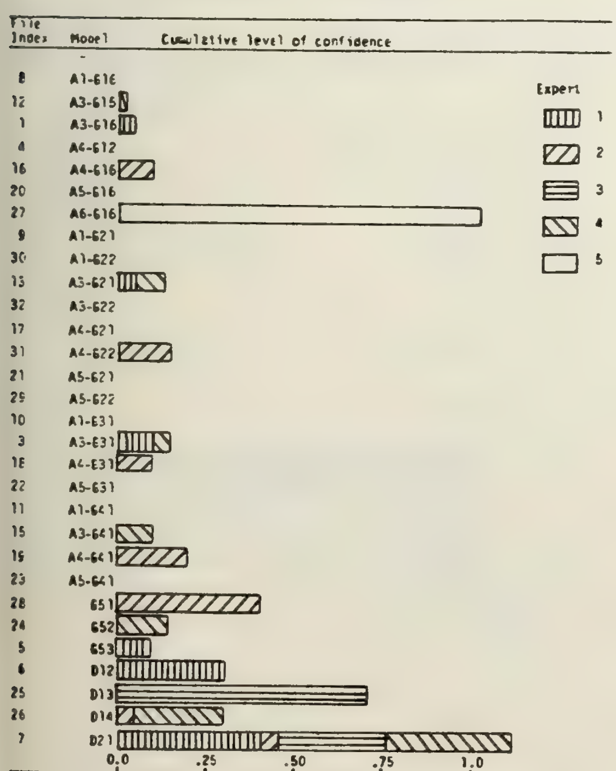
1. Accelerations e: for NE and using MM:



1. Accelerations f: for SE and using MM:



1. Accelerations g: for NC and using MM:



1. Accelerations h: for SC and using MM:

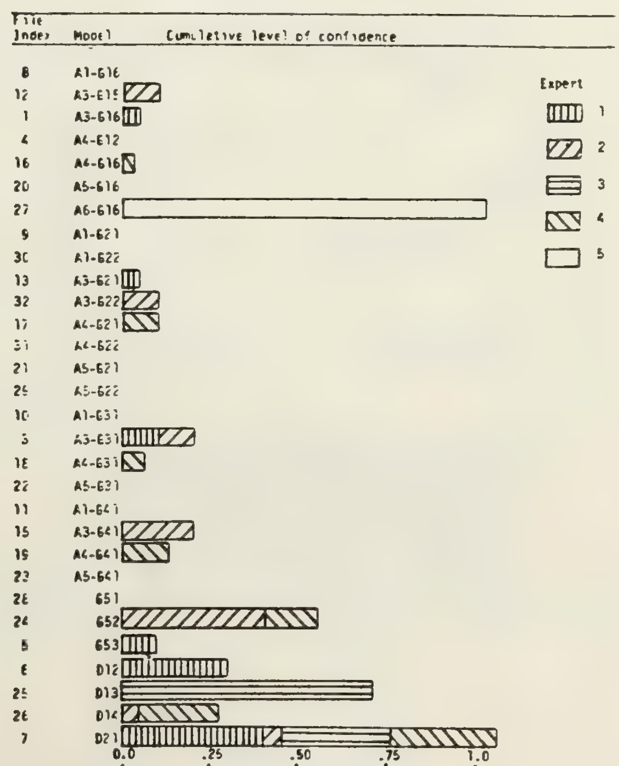
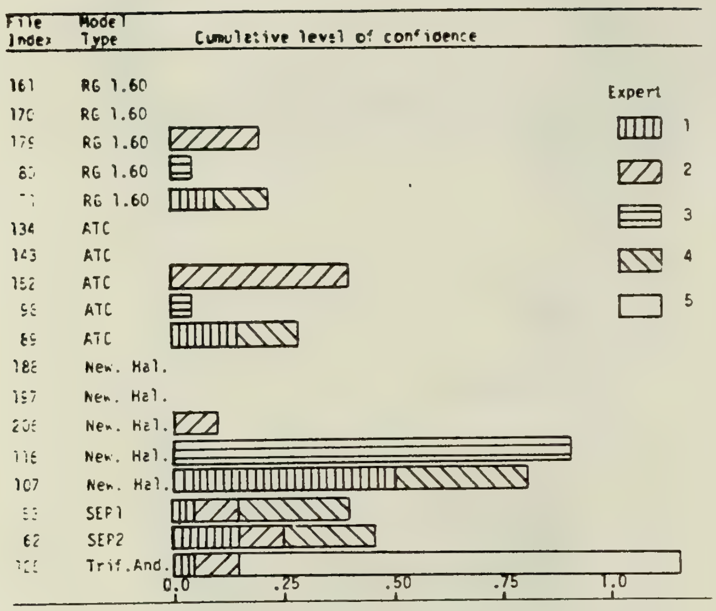
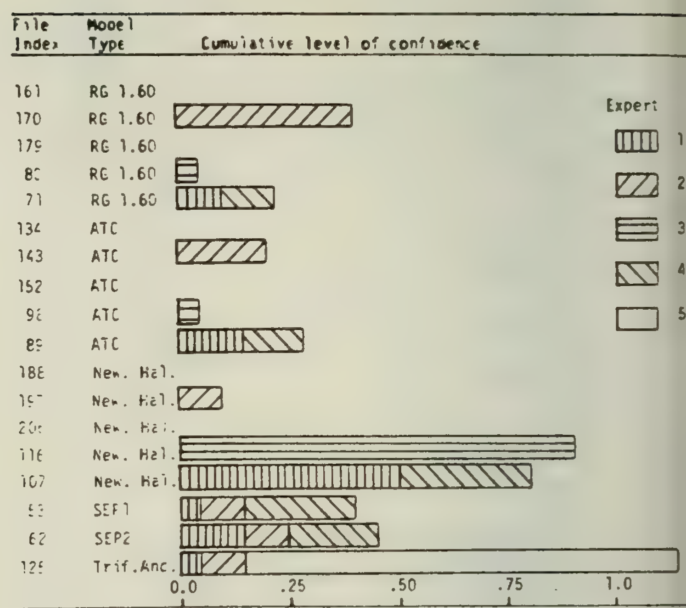


Table 2.5 (continued)

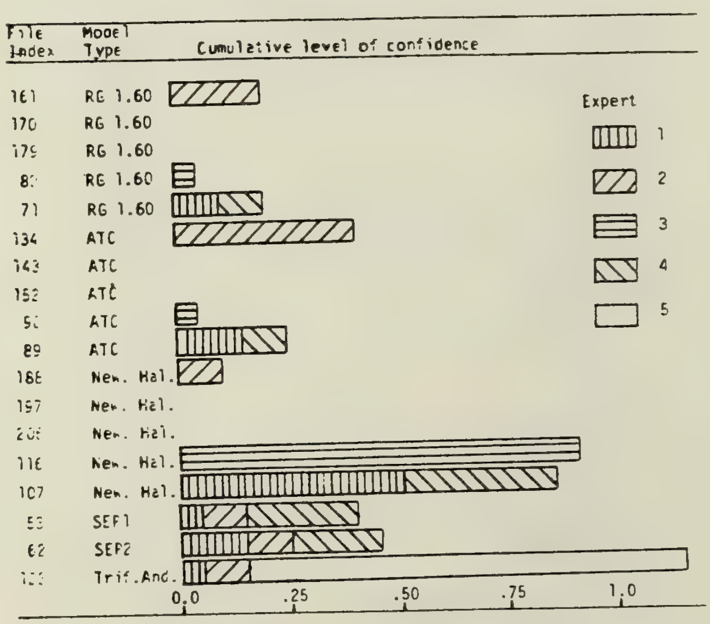
2. Spectra a: for NE and using m_b



2. Spectra b: for SE and using m_b



2. Spectra c: for NE and using m_b



2. Spectra d: for SE and using m_b

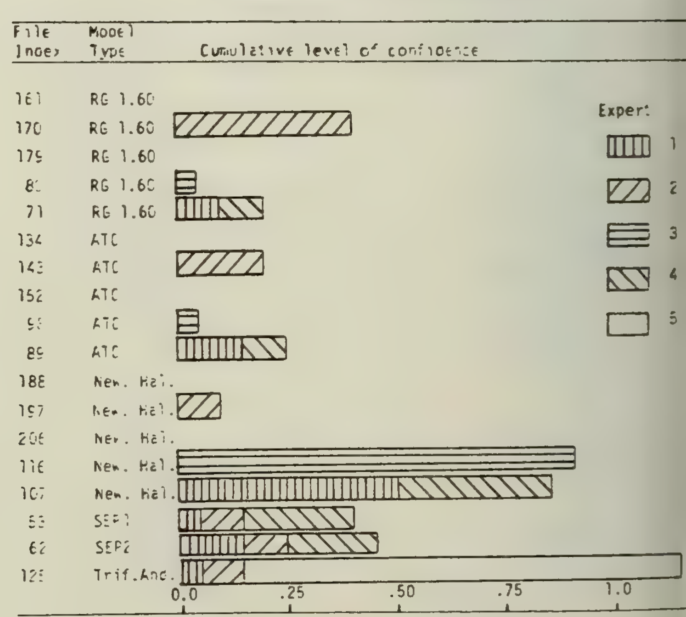
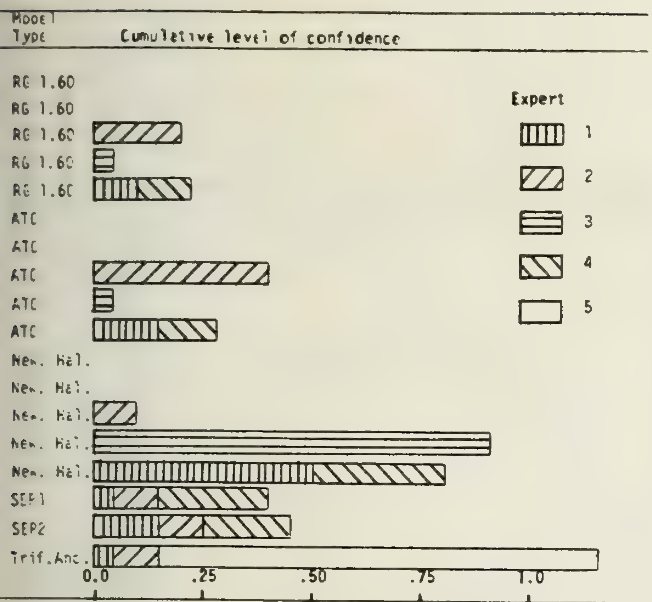
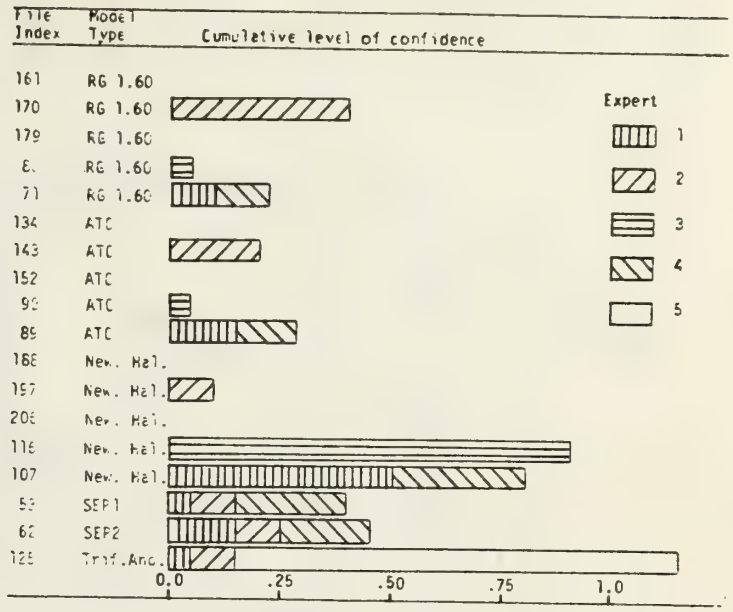


Table 2.5 (continued)

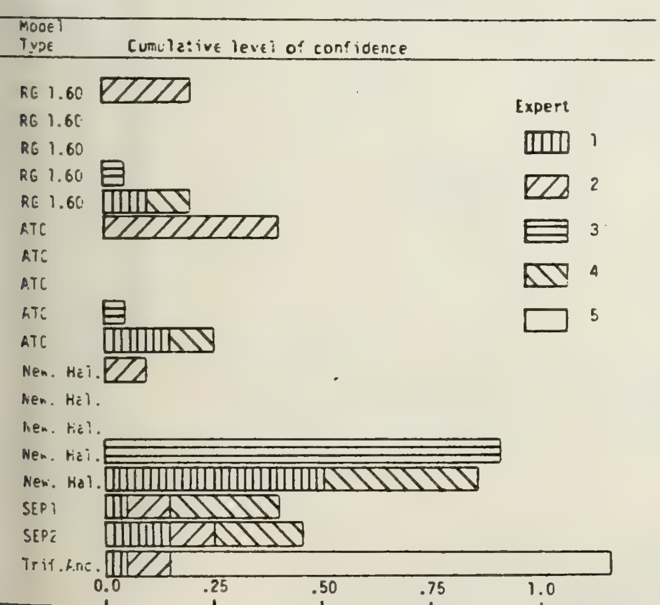
2. Spectra e: for NE and using MMI



2. Spectra f: for SE and using MMI



2. Spectra g: for NC and using MMI



2. Spectra h: for SC and using MMI

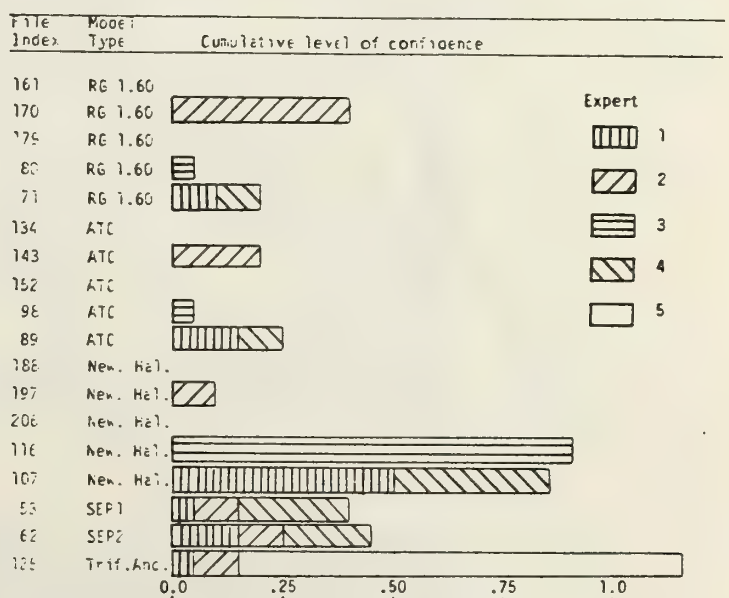


Table 2.5 (continued)

Fig. 2.1 Identification of four regions of the Eastern U.S. based on a compilation of the seismic zonation expert maps developed in this study, combined with a map of Q_o-contours from Singh & Herrmann (1983).

Plot Symbol	Model Number
1	1
2	4
3	8
4	12
5	16
6	20
7	27

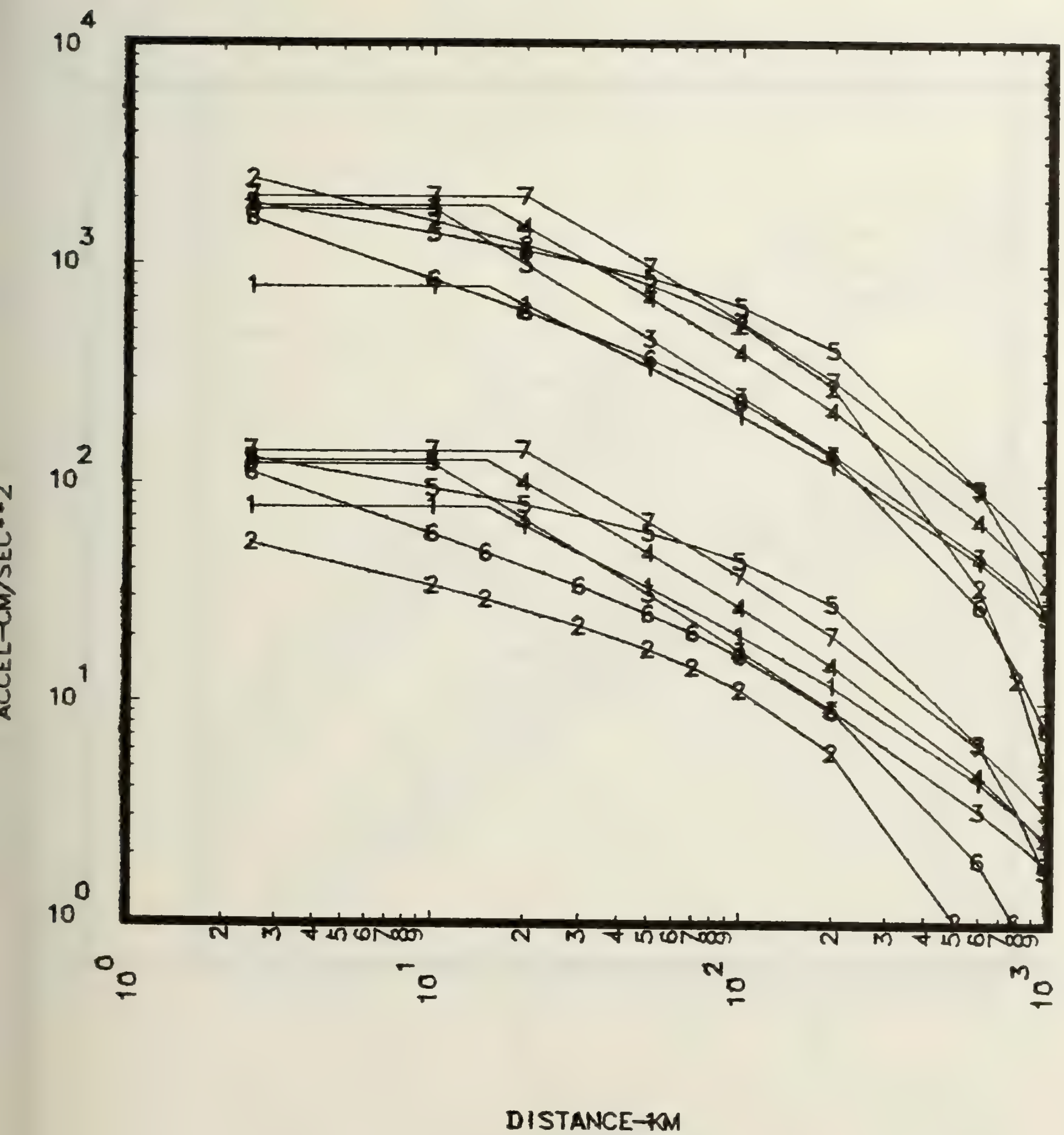


Fig. 2.2 Class 1 Intensity Based - No Weighting Acceleration Models Selected By GMP.

Plot Symbol	Mod Num
1	9
2	13
3	17
4	2
5	2
6	3
7	3
8	3

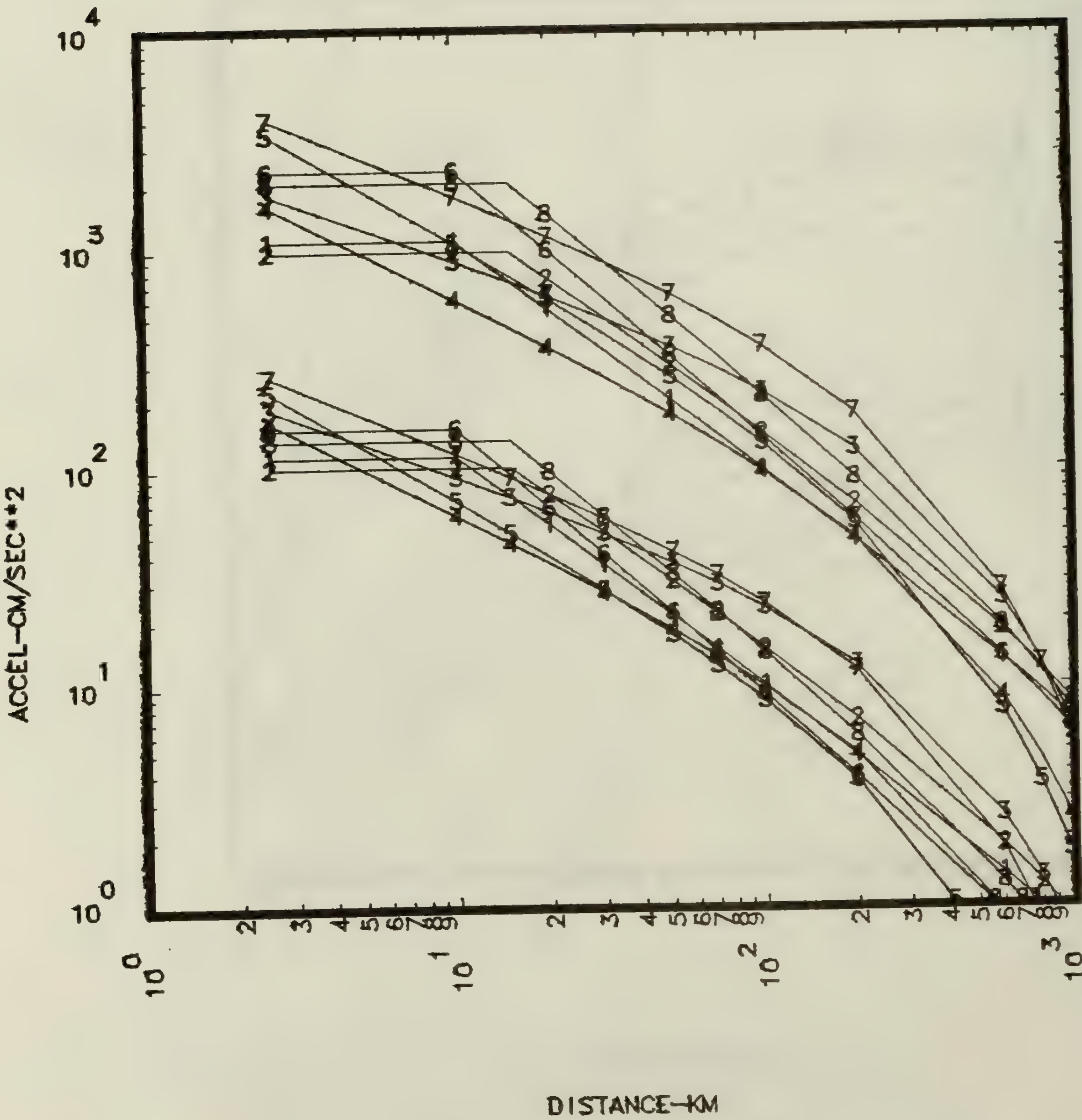


Fig. 2.3 Class 2 Intensity Based - Distance Weighting Acceleration Models Selected By GMP.

Plot Symbol	Model Number
1	3
2	10
3	18
4	22

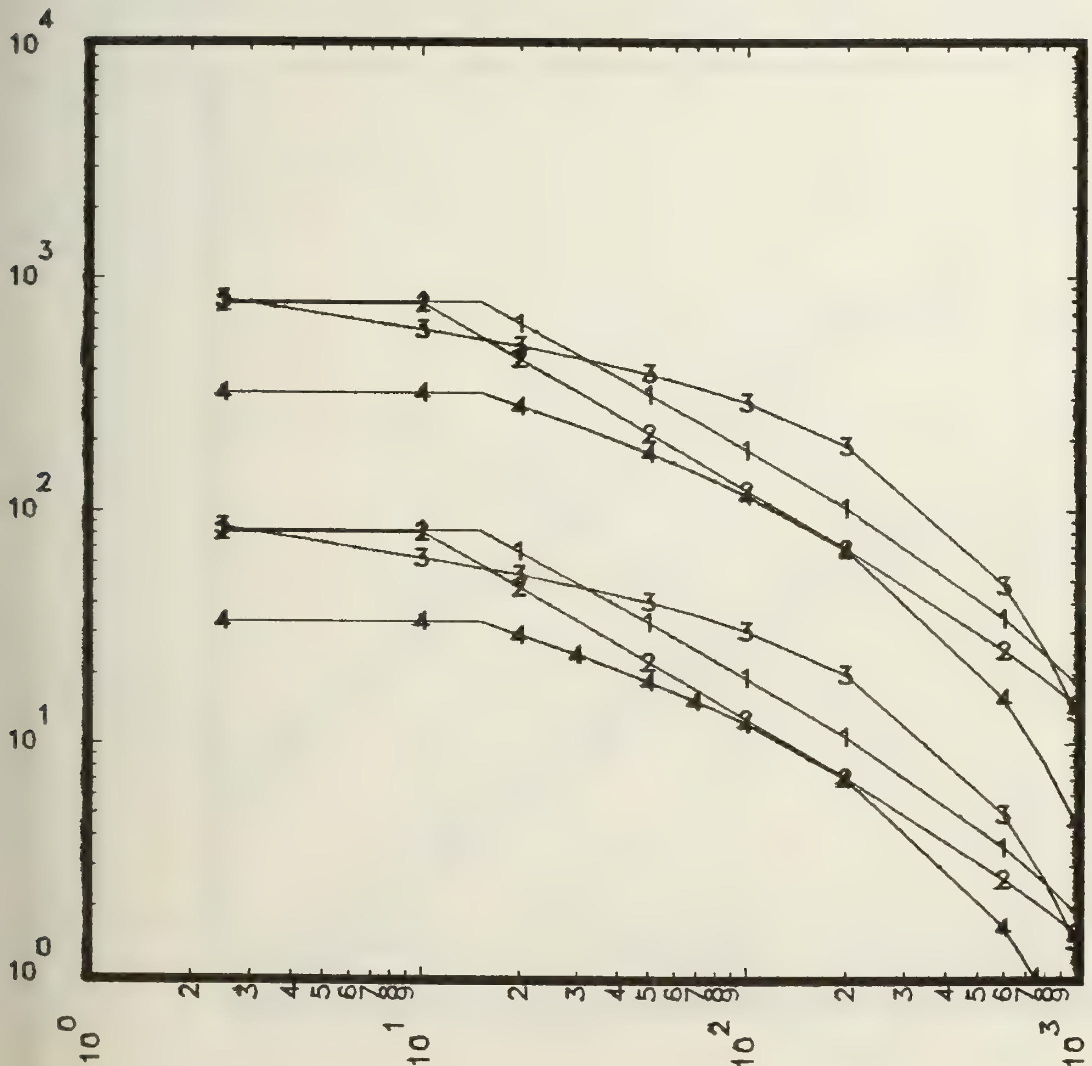


Fig. 2.4 Class 3 Intensity Based - Magnitude Weighting Acceleration Models Selected By GMP.

Plot Symbol	Mode Numb
1	11
2	15
3	19
4	23

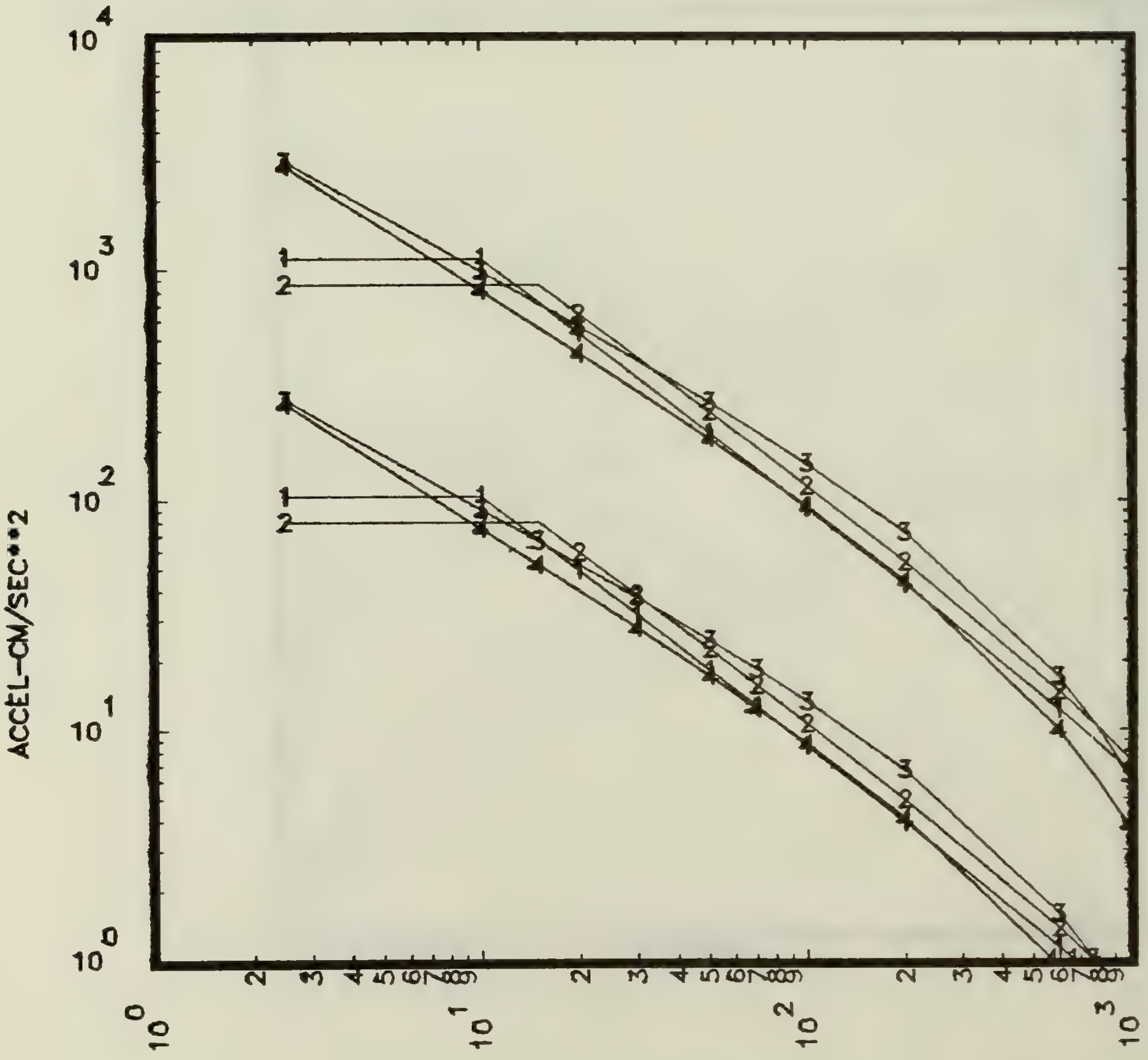


Fig. 2.5 Class 4 Intensity Based - Both Magnitude And Distance Weighting Acceleration Models Selected By GMP.

Plot Symbol	Model Number
1	5
2	24
3	28

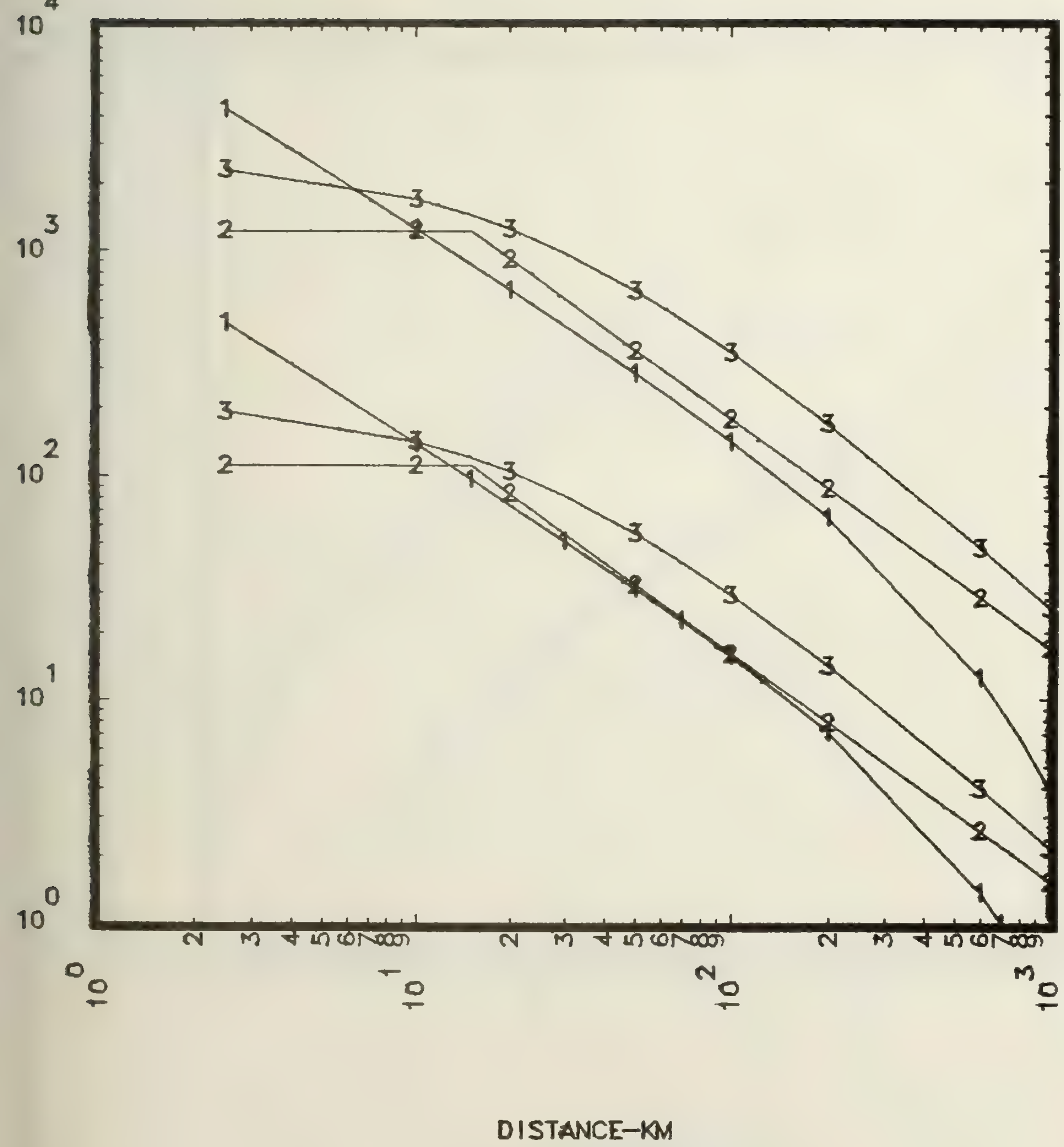


Fig. 2.6 Class 5 Intensity Based - Semi-Empirical Acceleration Models Selected By GMP.

Plot Symbol	Mod Num
1	6
2	25
3	26
4	7

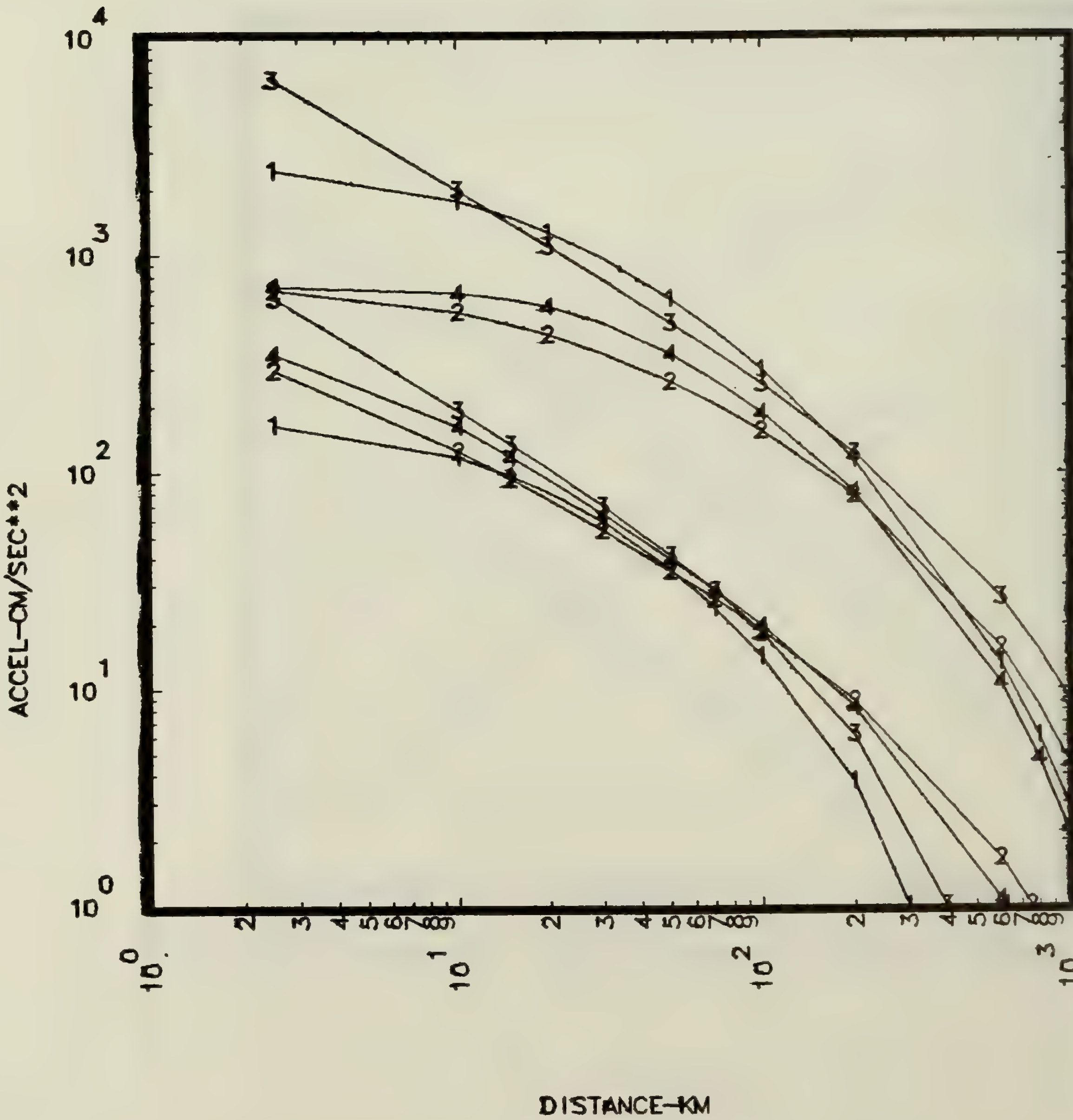


Fig. 2.7 Classes 6 & 7 - Direct Acceleration Models Selected By GMP.

Plot Symbol	Model Number
2	38
3	33
4	44
5	47

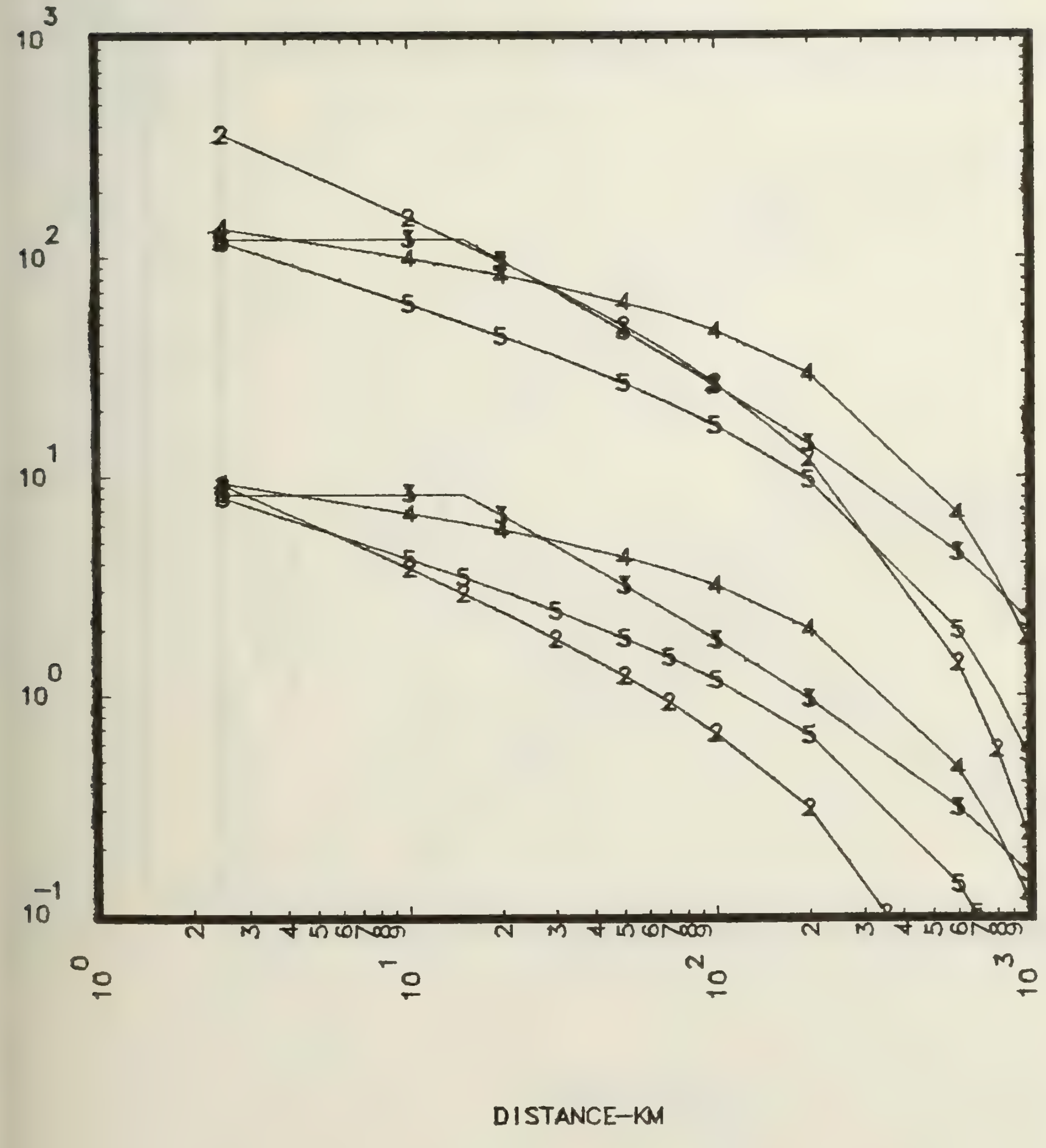


Fig. 2.8 Class 1 Intensity Based - No Weighting Velocity Models Selected by GMP.

Plot Symbol	Model Number
1	34
2	39
3	42
4	45
5	48

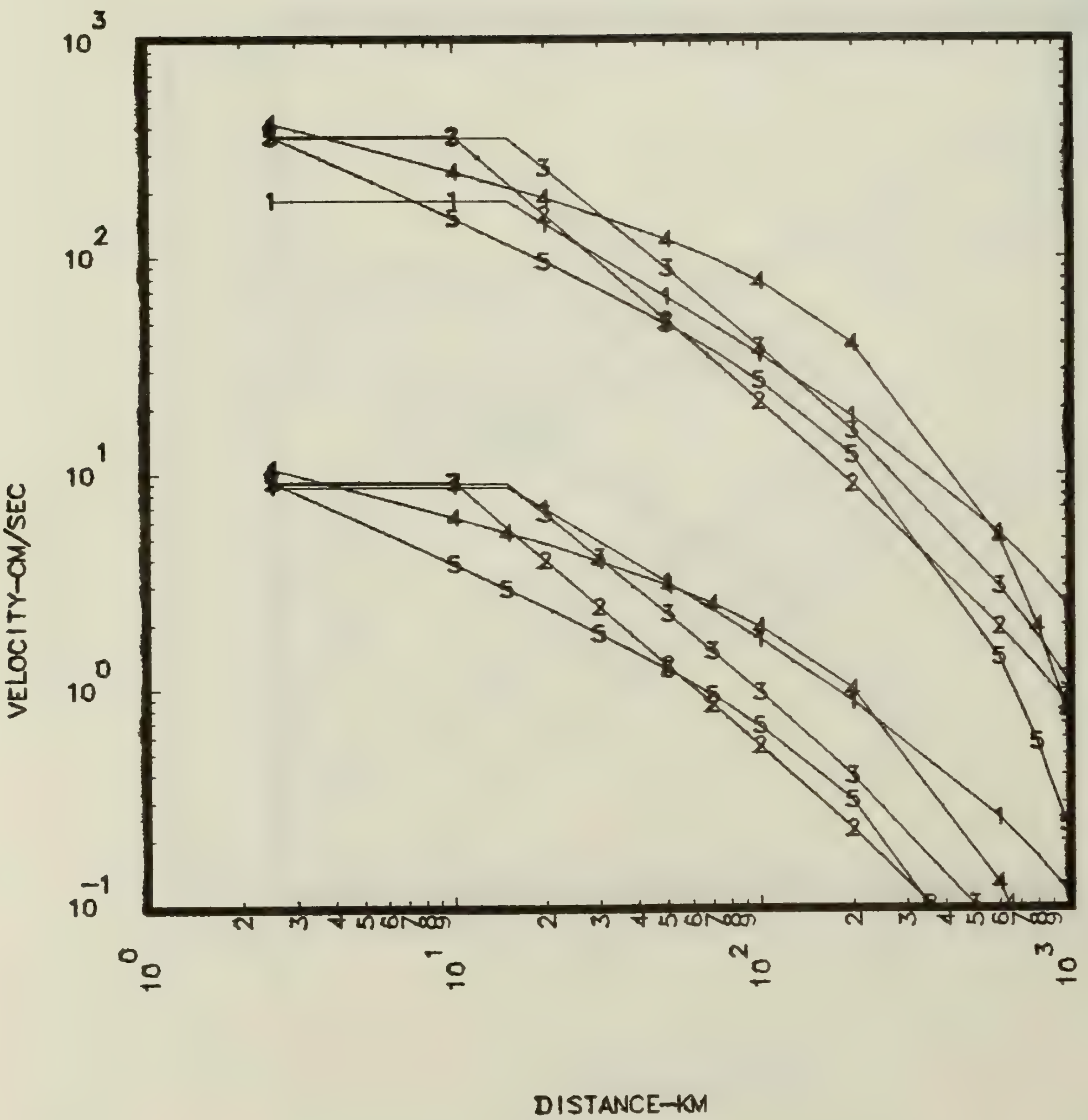


Fig. 2.9 Class 2 Intensity Based - Distance Weighting Velocity Models Selected By GMP.

Plot Symbol	Model Number
2	40
3	35
4	46
5	49

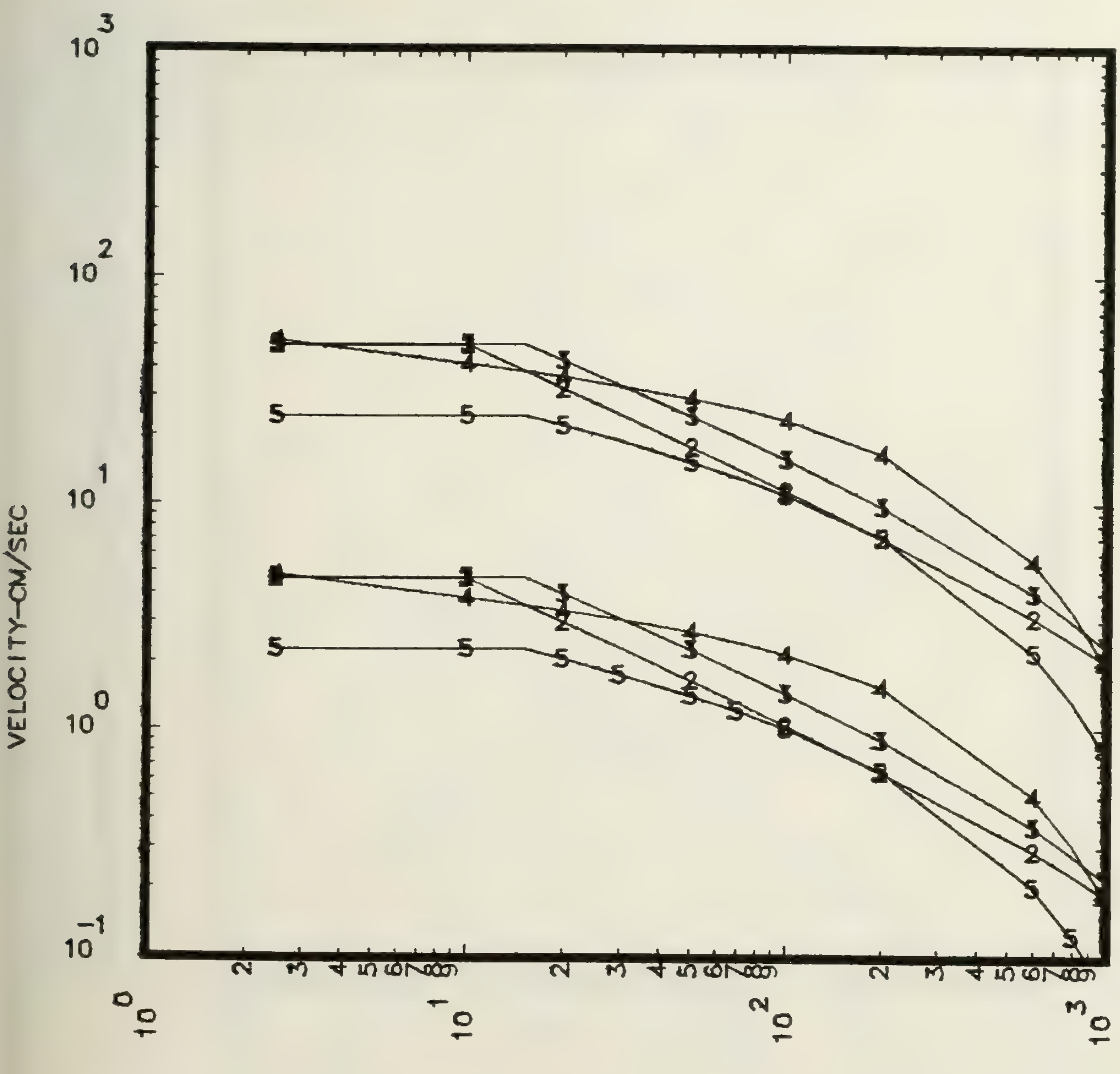


Fig. 2.10 Class 3 Intensity Based - Magnitude Weighting Velocity Models Selected By GMP.

Plot Symbol	Model Numbe[r]
1	36
2	50
3	52

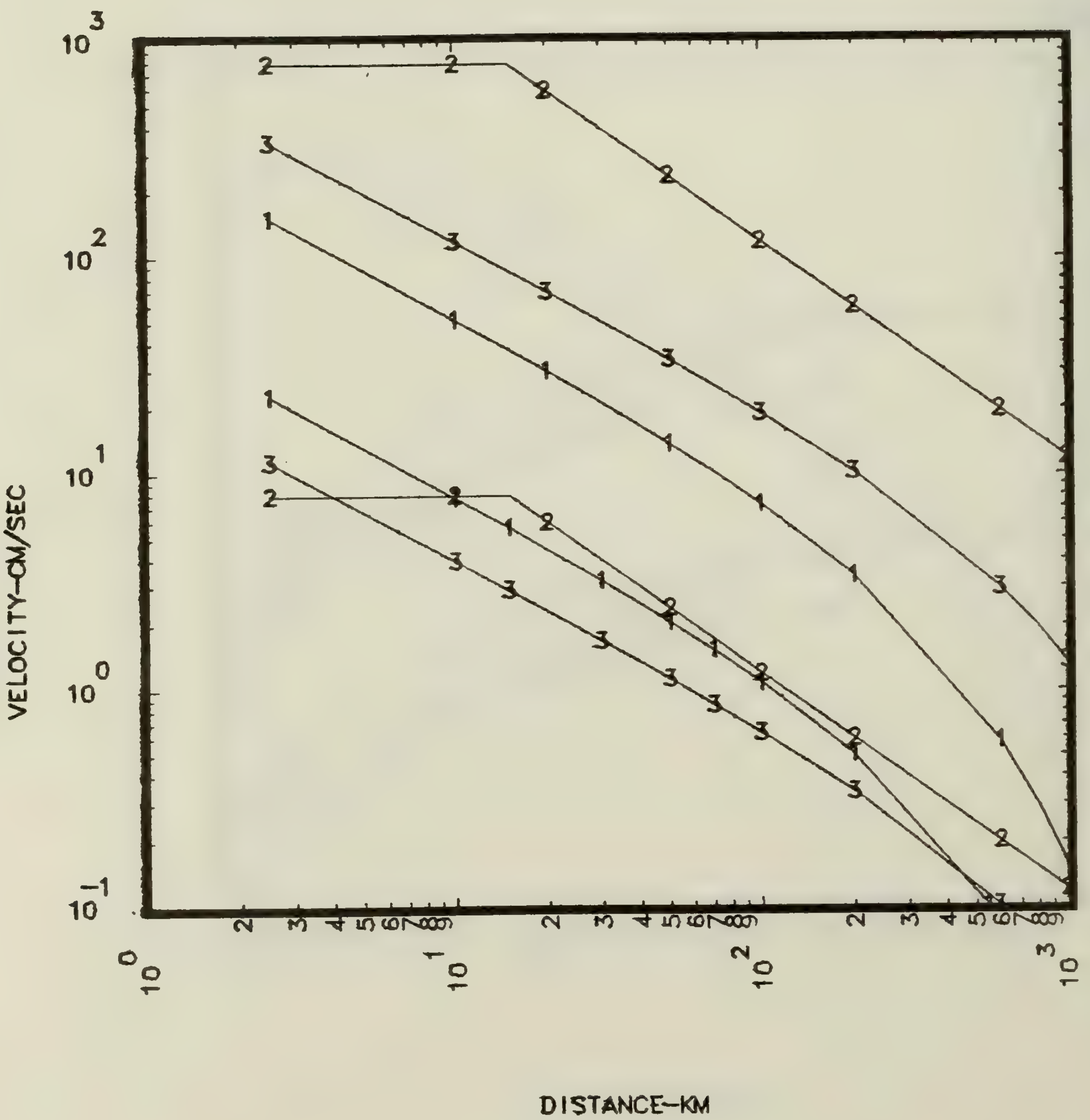


Fig. 2.11 Class 5 Intensity Based - Semi-Empirical Velocity Models Selected By GMP.

Plot Symbol	Model Number
1	51
2	37

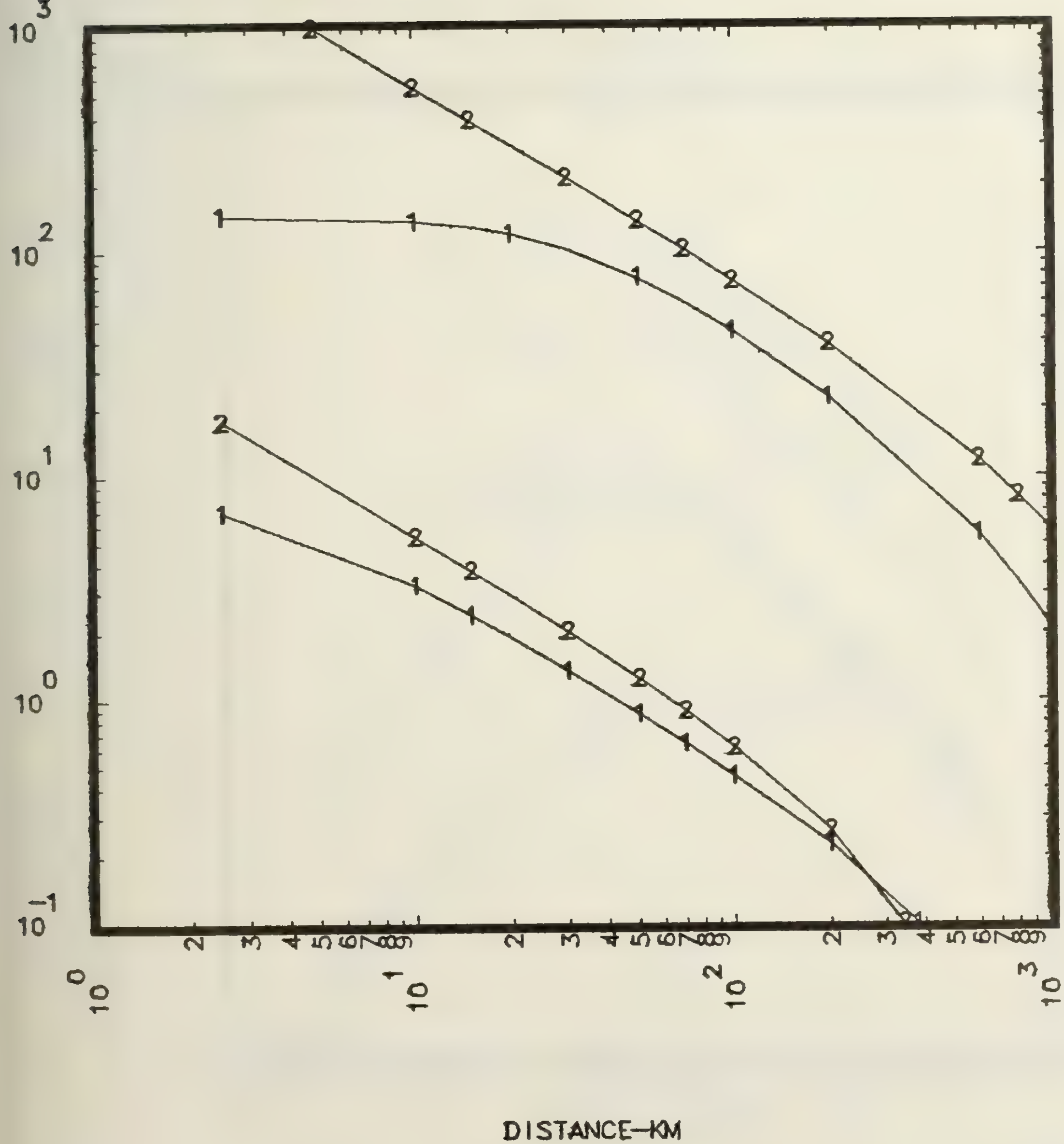


Fig. 2.12 Classes 6 & 7 Direct Velocity Models Chosen By GMP.

Plot Symbol	Model Numbe
1	71
2	80
3	161
4	170
5	179

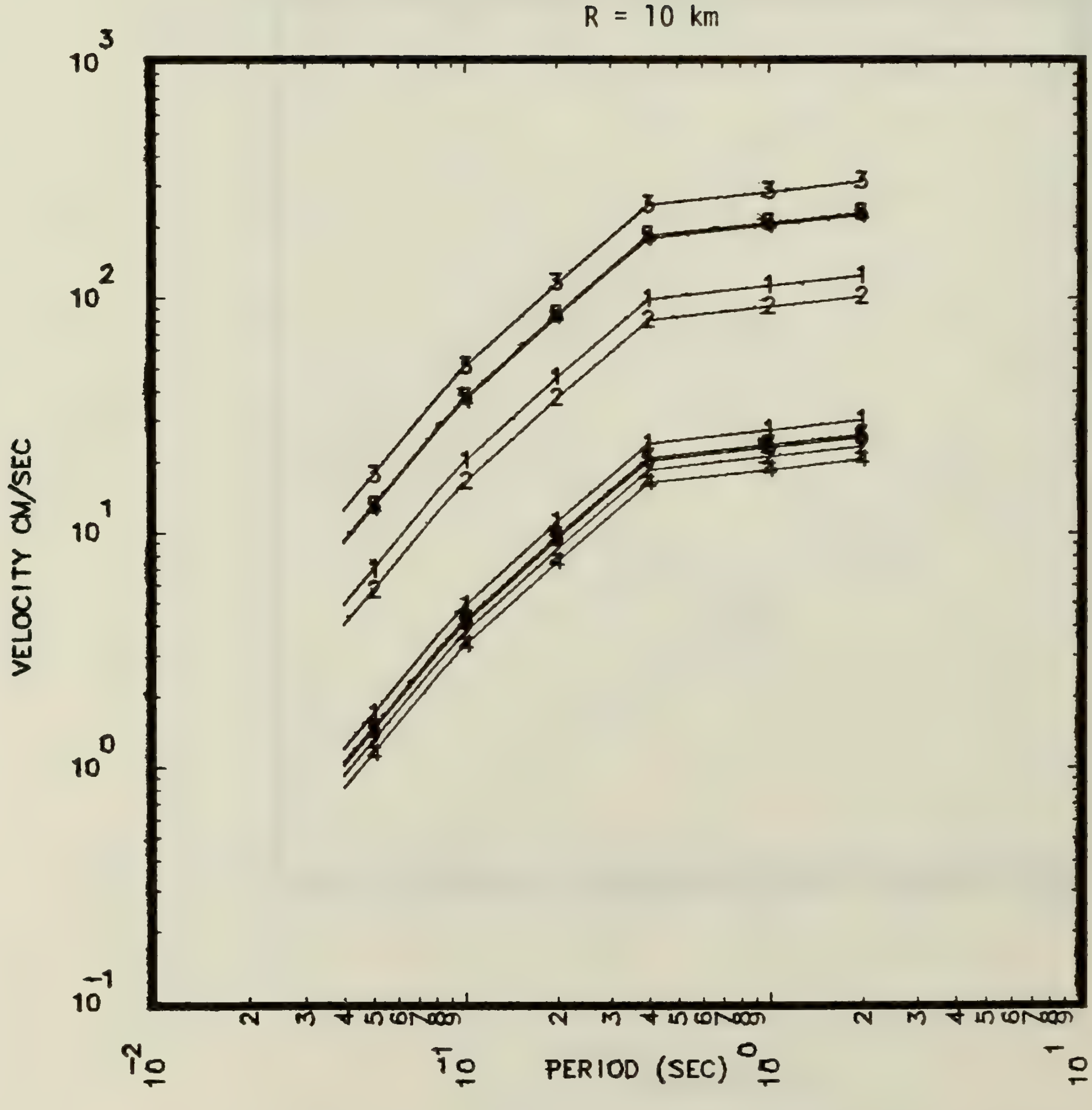


Fig. 2.13a Class RSI Median R.G. 1.60 Spectral Models Chosen By GMP.

Plot Symbol	Model Number
1	71
2	80
3	161
4	170
5	179

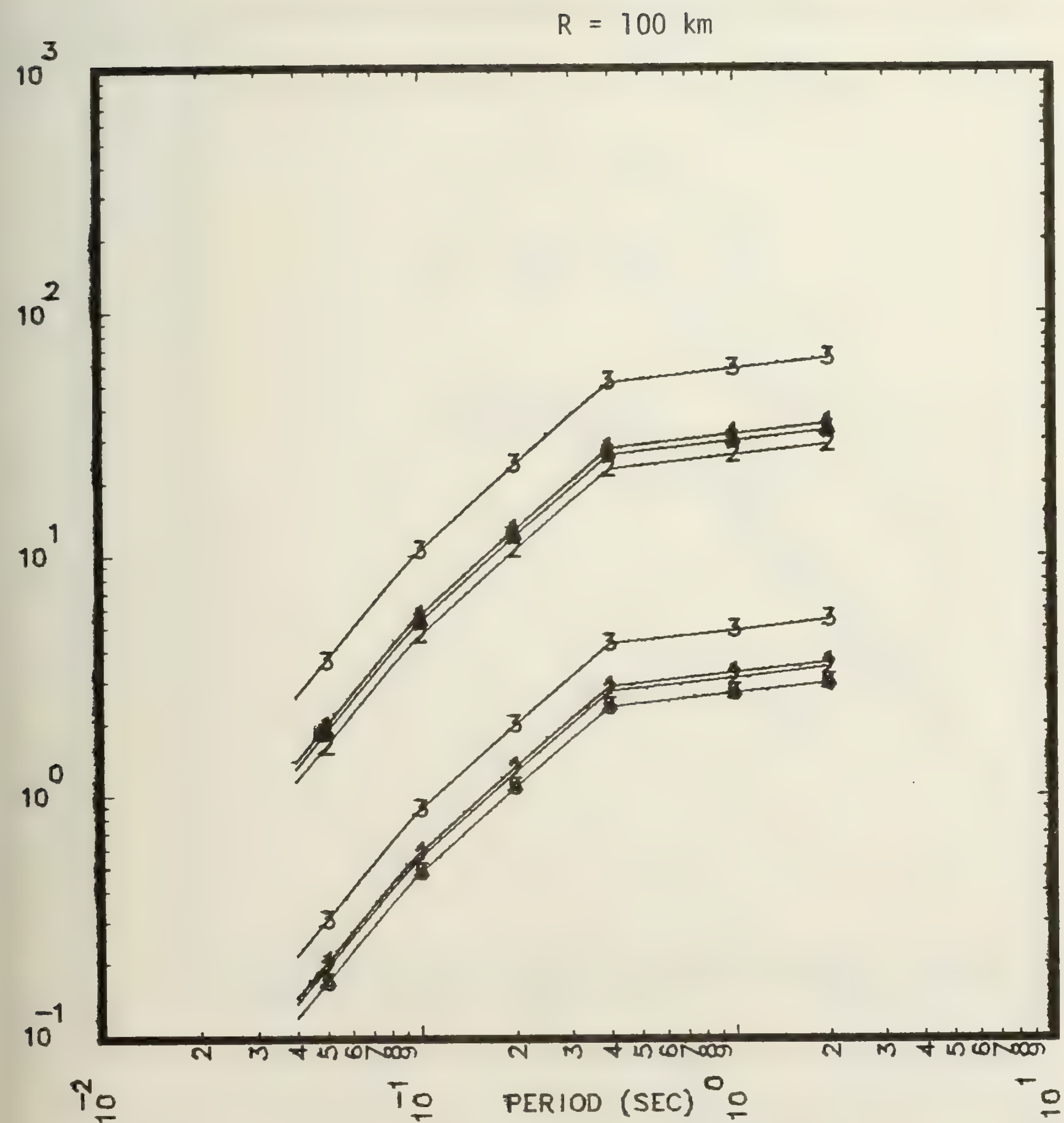


Fig. 2.13b Class RSI Median R.G. 1.60 Spectral Models Chosen By GMP.

Plot Symbol	Model Numbe
1	89
2	98
3	134
4	143
5	152

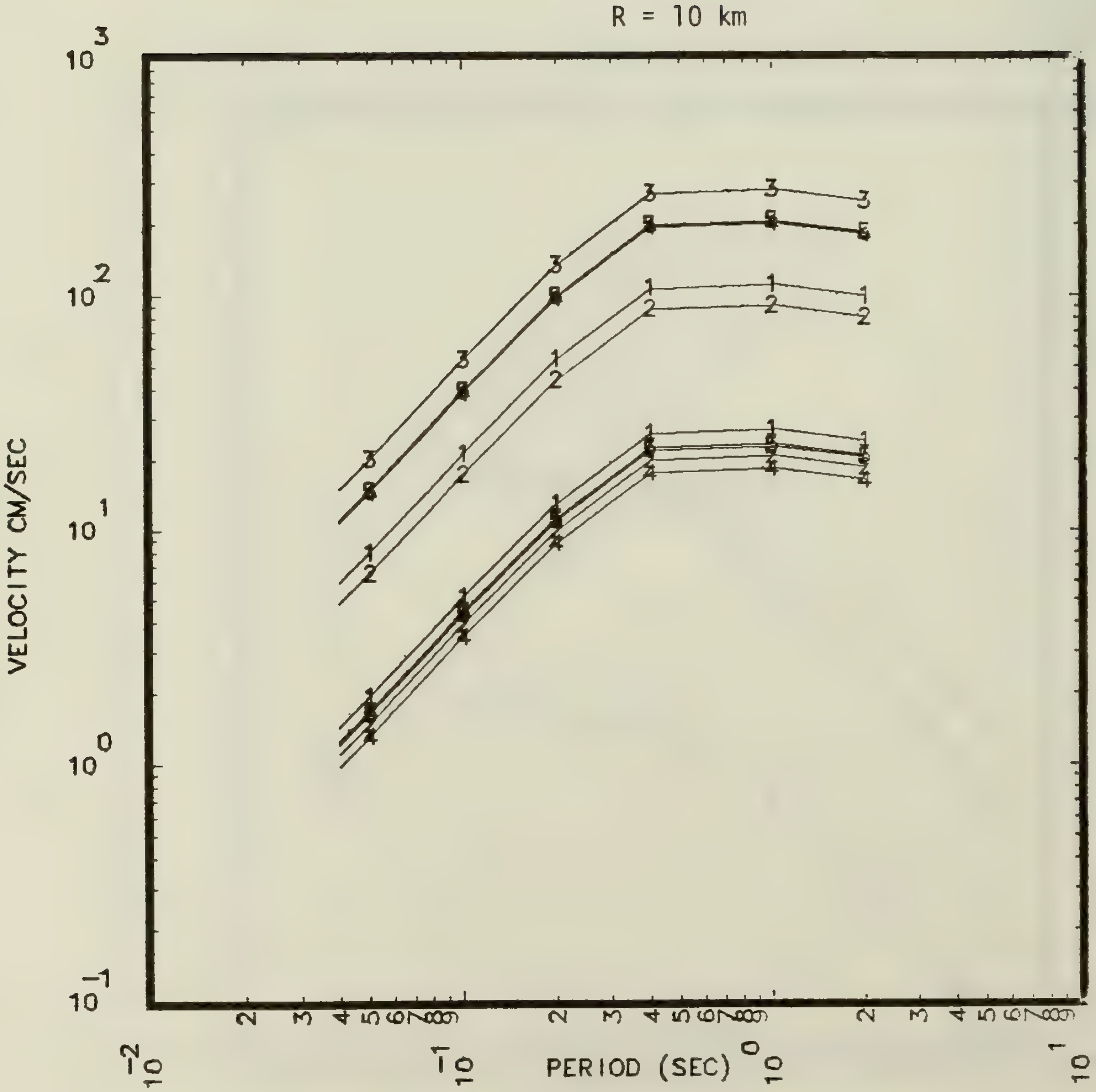


Fig. 2.14a Class RS2 ATC Spectral Models Chosen By GMP.

Plot Symbol	Model Number
1	89
2	98
3	134
4	143
5	152

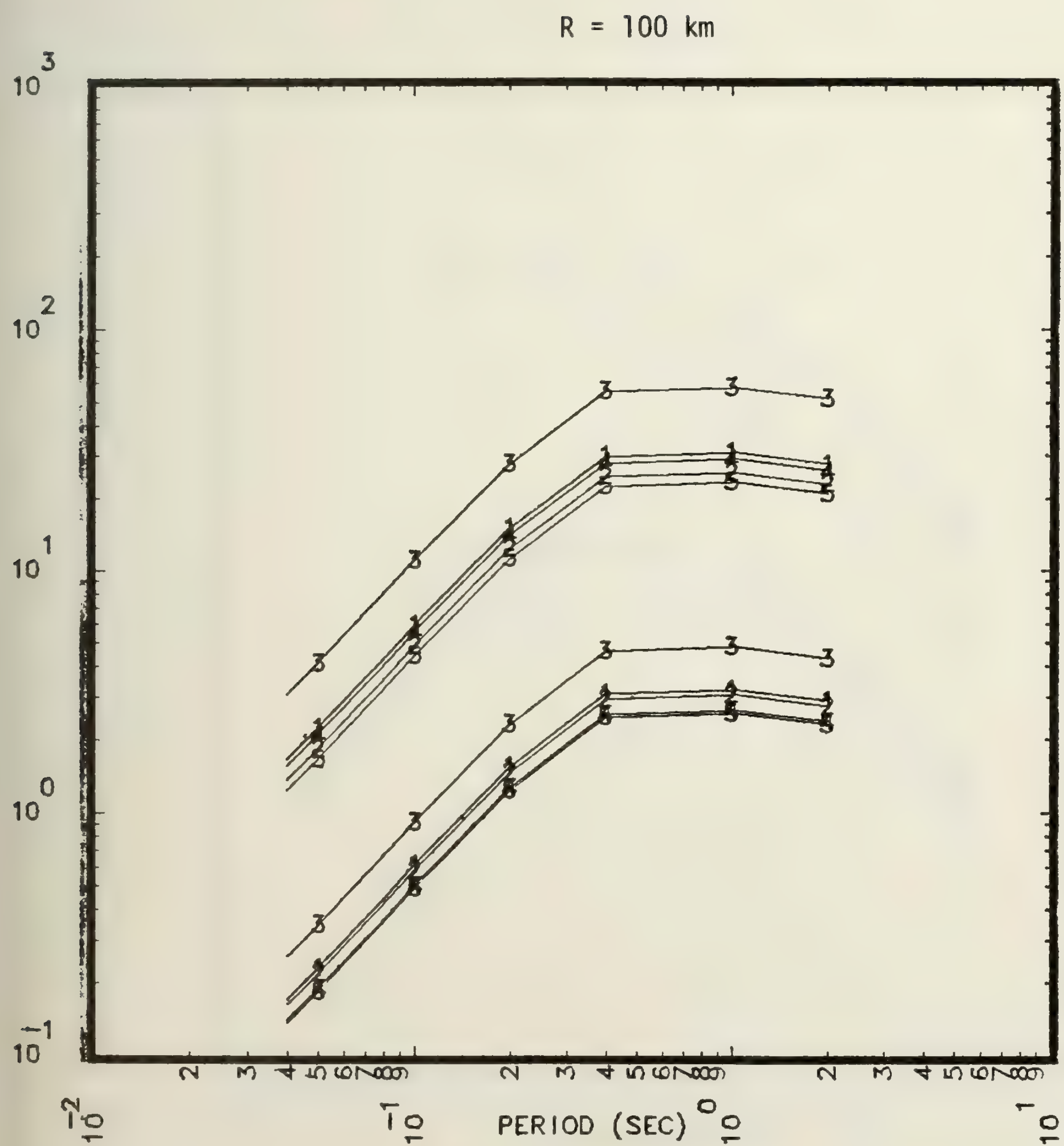


Fig. 2.14b Class RS2 ATC Spectral Models Chosen By GMP.

Plot Symbol	Model Number
1	107
2	116
3	188
4	197
5	206

R = 10 km

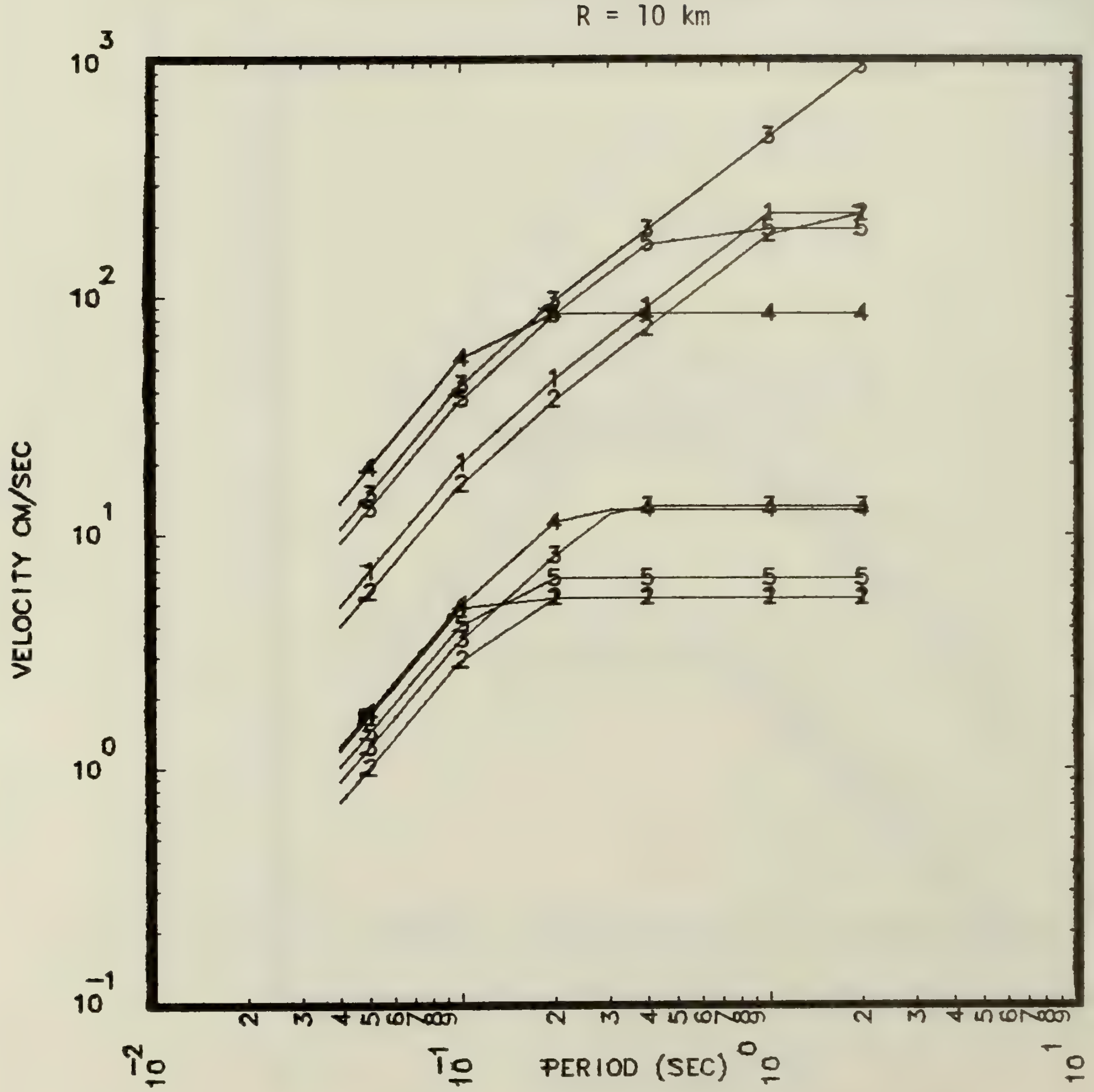


Fig. 2.15a Class RS3 Newmark-Hall Spectral Models Chosen By GMP.

Plot Symbol	Model Number
1	107
2	116
3	188
4	197
5	206

R = 100 km

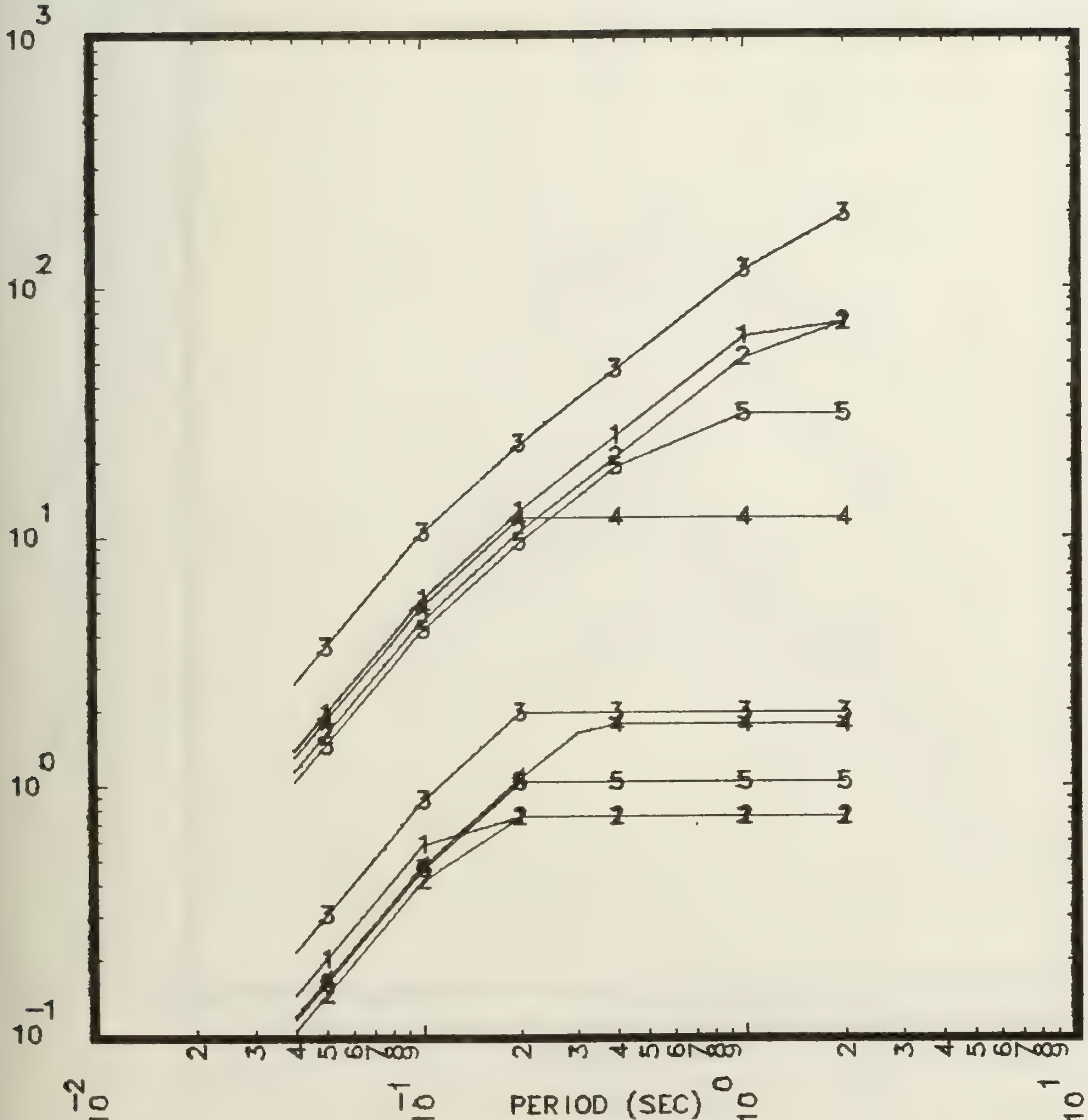


Fig. 2.15b Class RS3 Newmark-Hall Spectral Models Chosen By GMP.

Plot Symbol	Model Number
1	53
2	62
3	125

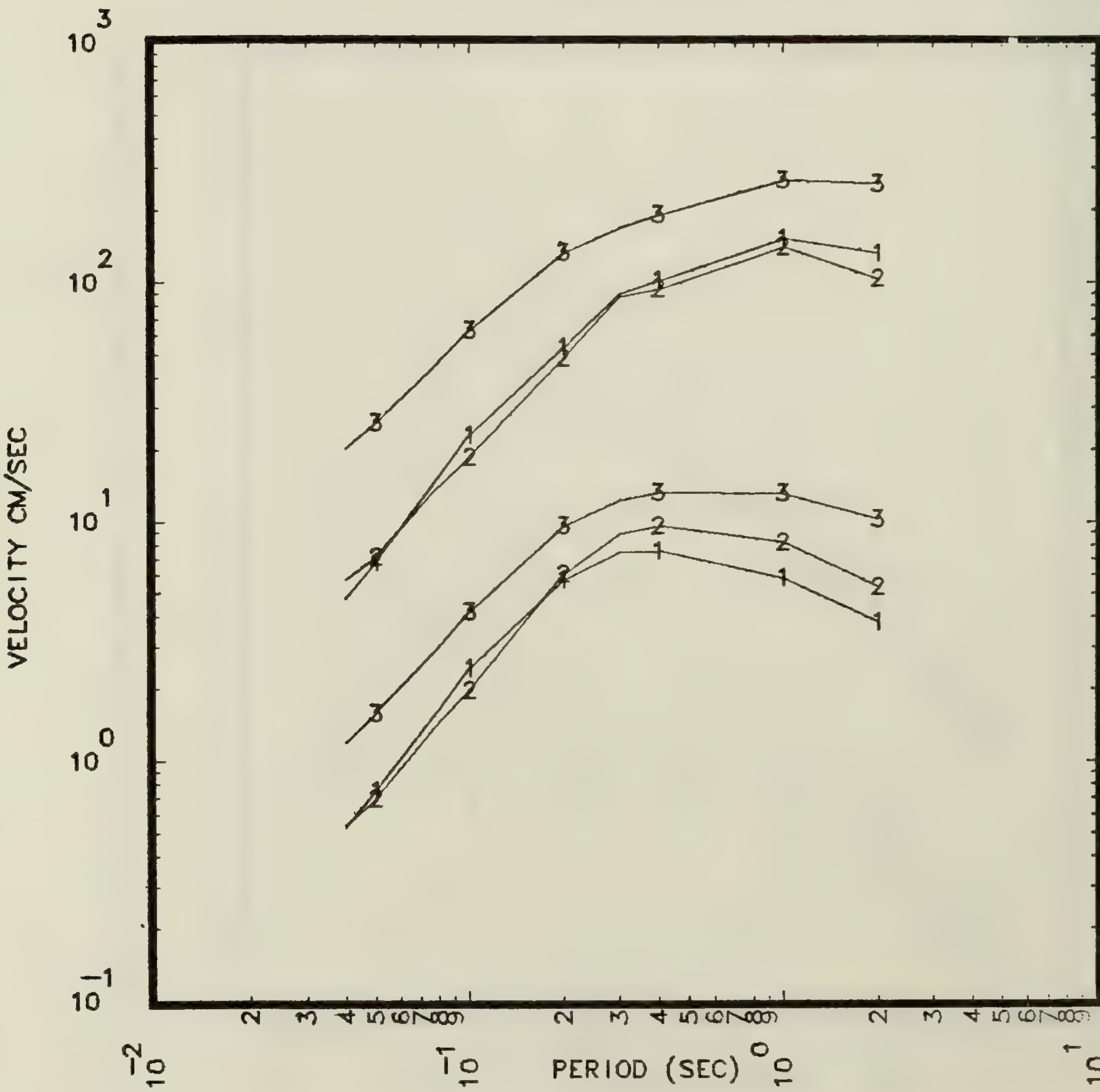


Fig. 2.16a Classes RS4, RS5 & RS6 Spectral Models Chosen By GMP.

Plot Symbol	Model Number
1	53
2	62
3	125

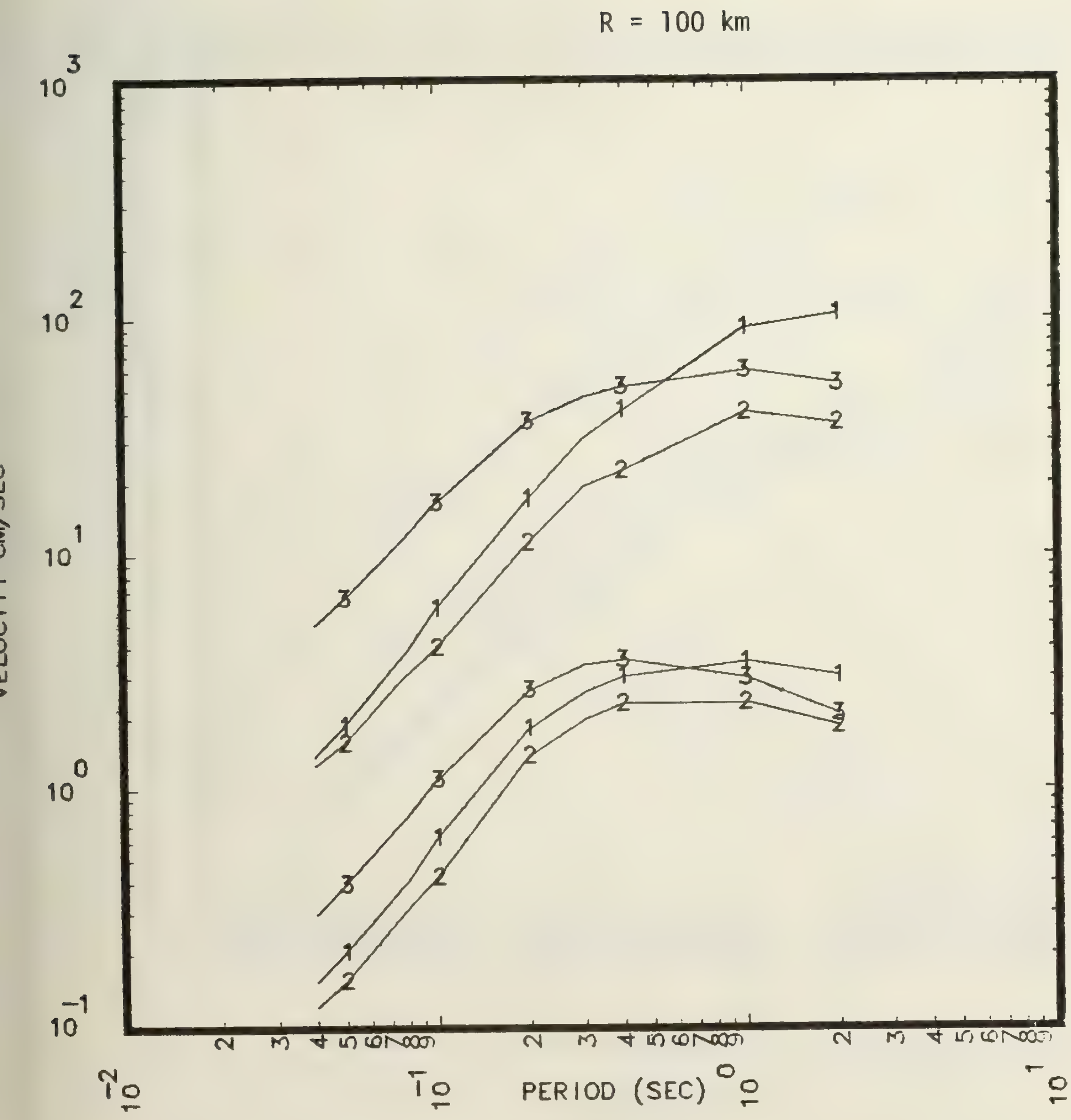


Fig. 2.16b Classes RS4, RS5 & RS6 Spectral Models Chosen By GMP.

Plot Symbol	Mode Numb
1	5
2	7
3	24
4	25
5	27
6	28

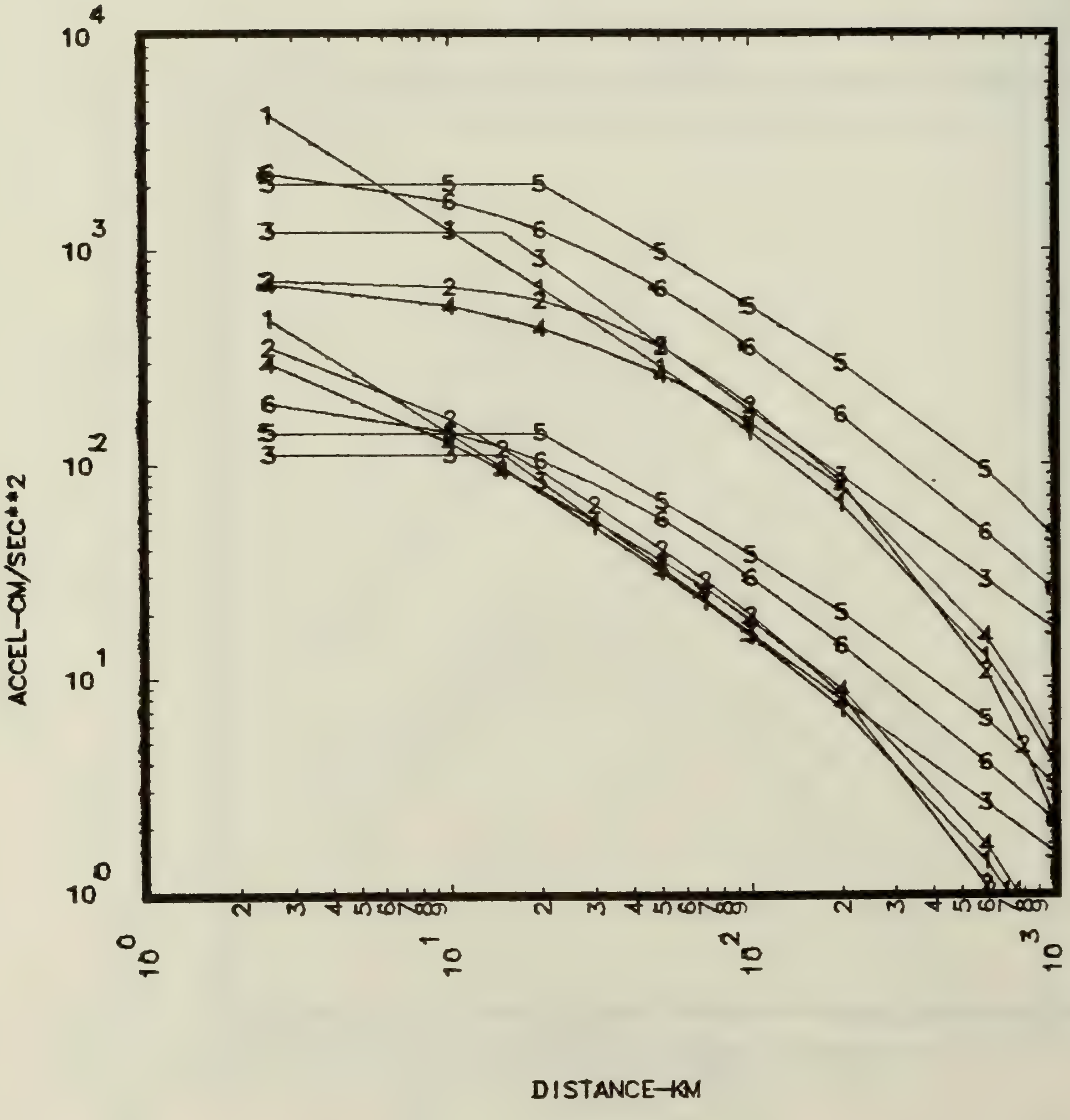


Fig. 2.17 Best Estimate Acceleration Models Selected By GMP.

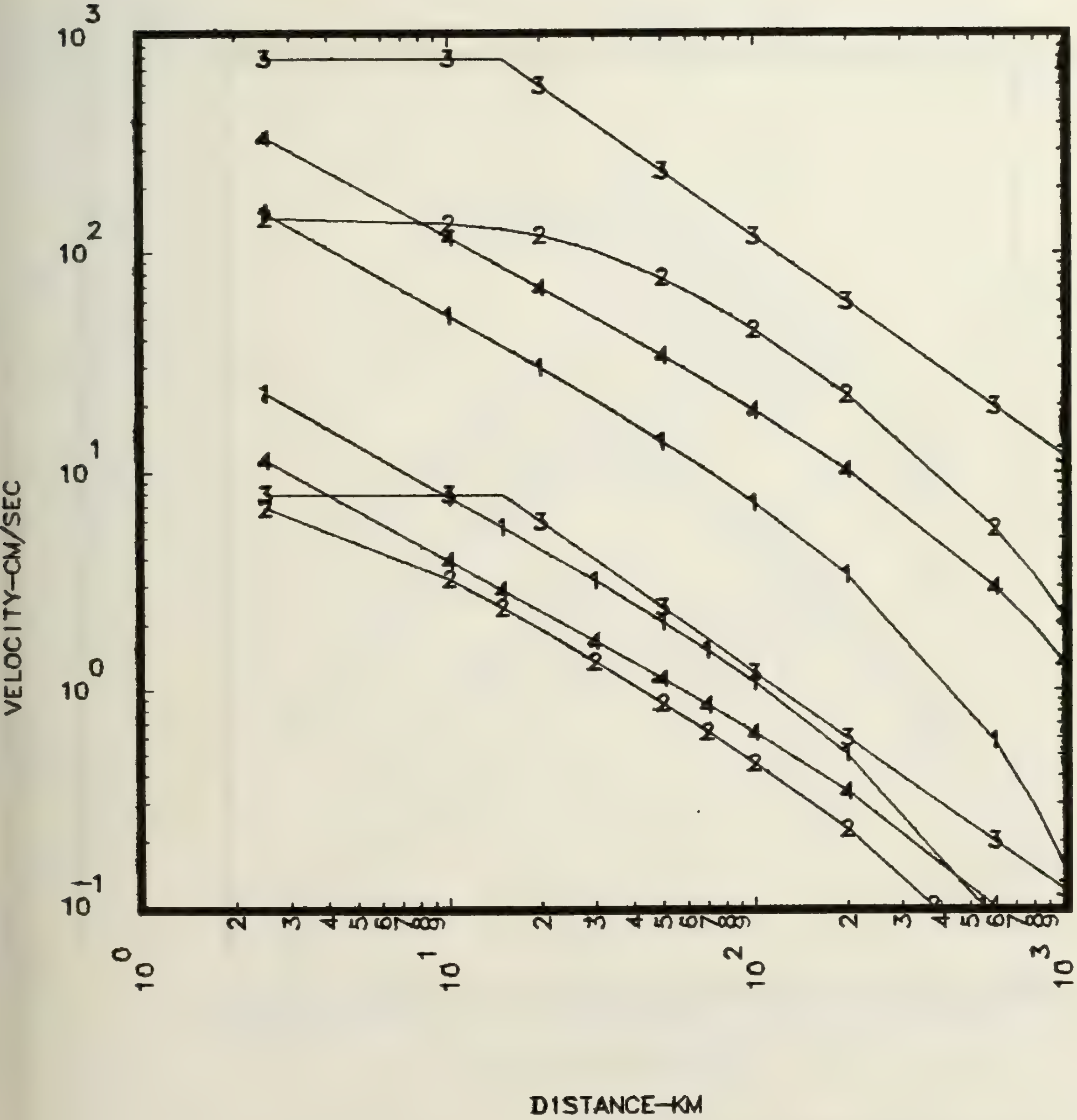


Fig. 2.18 Best Estimate Velocity Models Selected By GMP.

Plot Symbol	Model Number
1	107
2	116
3	125
4	134
5	152
6	170

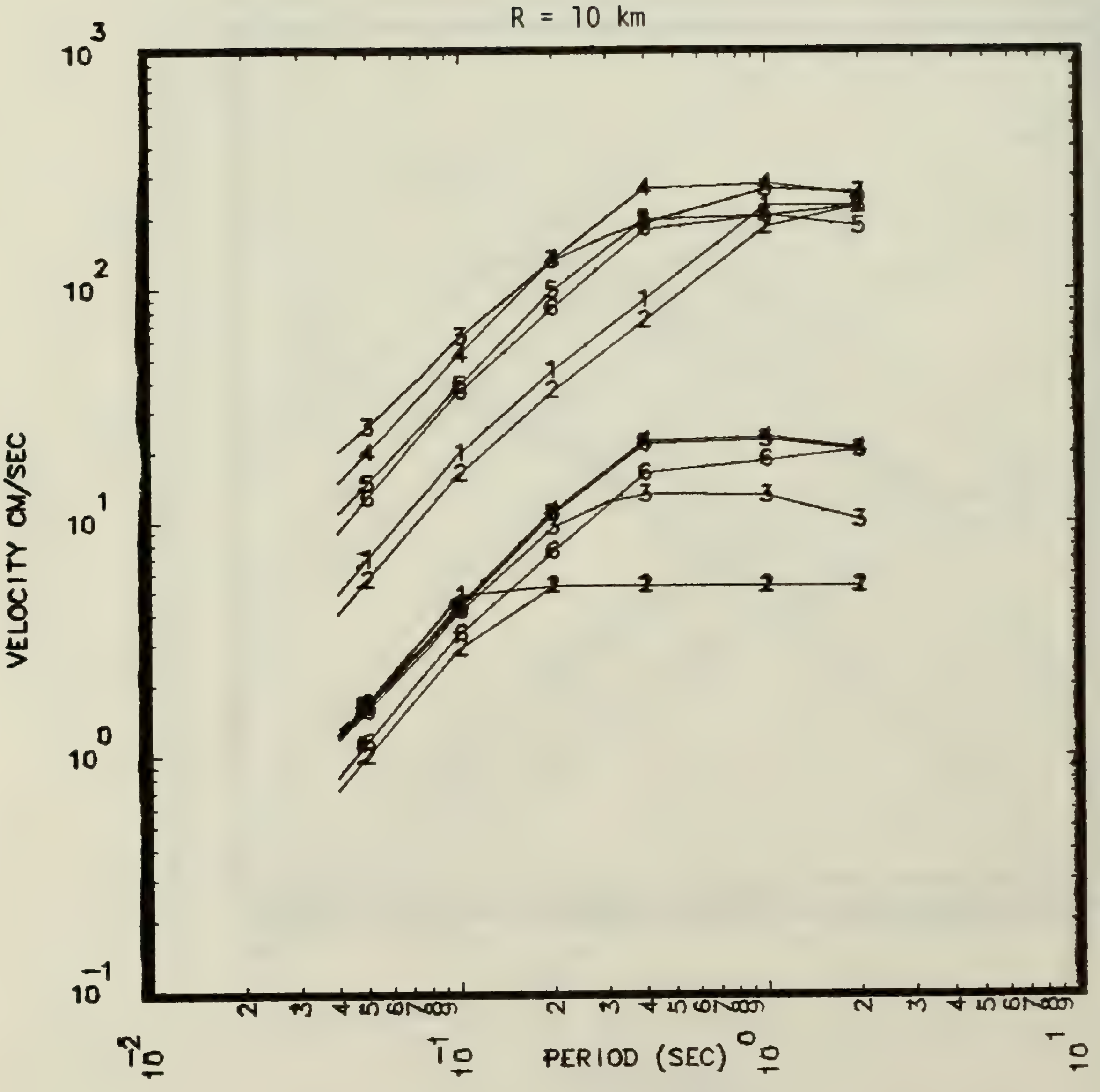


Fig. 2.19a Best Estimate Spectral Models Selected By GMP.

Plot Symbol	Model Number
1	107
2	116
3	125
4	134
5	152
6	170

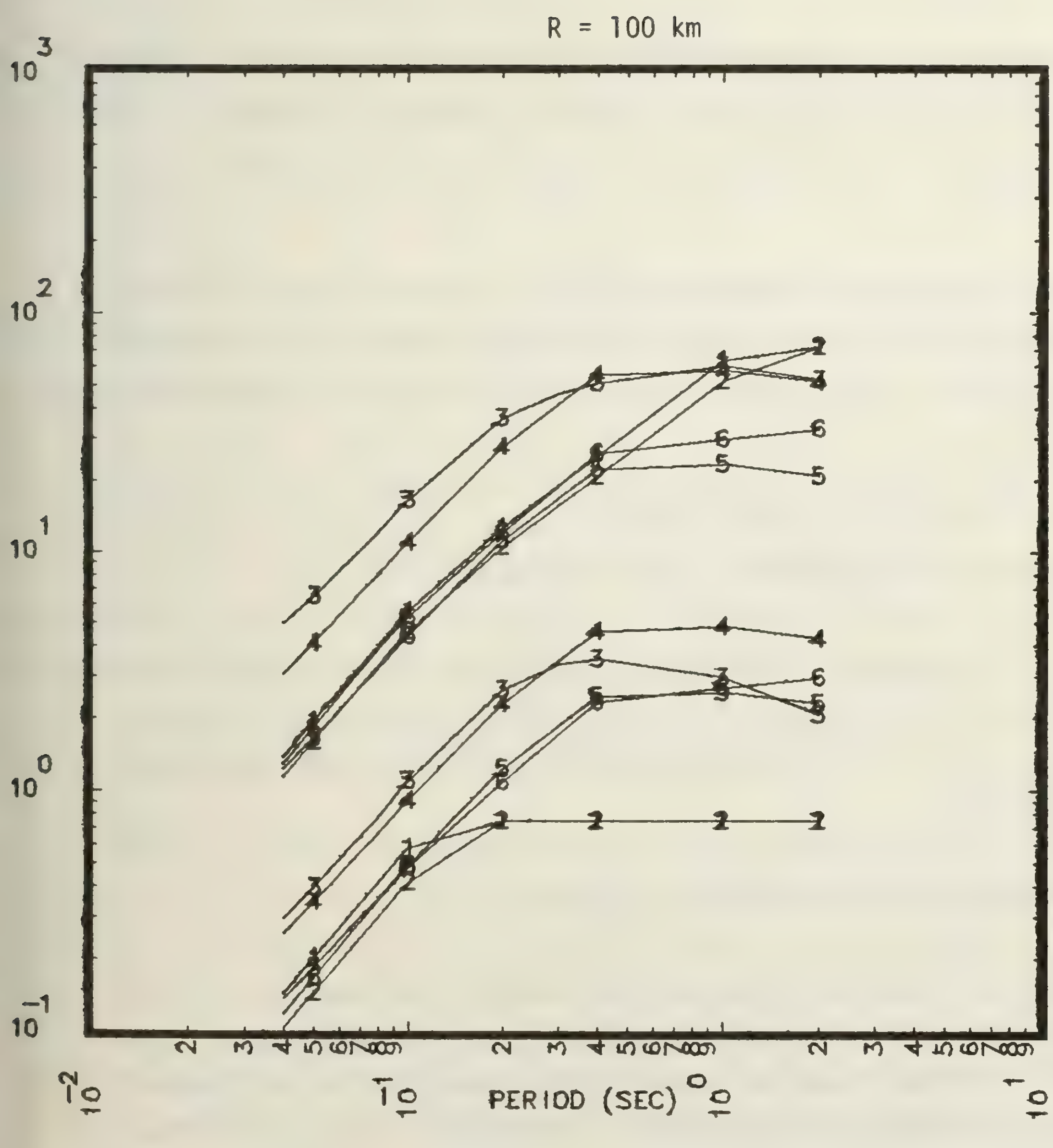


Fig. 2.19b Best Estimate Spectral Models Selected By GMP.

3. IMPACT OF THE GROUND MOTION MODELS ON THE HAZARD

3.1 Introduction

The impact of the ground motion models on the hazard has been described and analyzed in detail in the Interim Report. However, the availability of an additional set of models provided to us by expert 2 made it necessary to update the analysis.

We selected two sites, Braidwood and Millstone, very different in their seismic environment, and three seismicity experts, experts 1, 6 and 12 in an effort to cover the widest possible spectrum of cases with a limited computational effort.

- For each site and each of the 3 seismicity experts, we show the hazard calculated with the B.E. ground motion model of each of the 5 ground motion experts for the acceleration and for the pseudo velocity spectra.

- Then for each ground motion expert we show the hazard calculated with each one of the ground motion models provided, considering that all the other parameters (seismicity, maps) are random.

- Finally, for these two sites we give the hazard calculated by combining all the ground motion experts, but still with only the 3 seismicity experts' input selected above and letting all the random parameters free of varying.

3.2 Best Estimate (B.E.) Ground Motion Models

The hazard was calculated for the two example sites and 3 seismicity experts by assigning to each random variable its best estimate value. These calculations allow to make relative comparisons between the various ground motion models for a given set of maps and for known set values of the other parameters. Figures 3.1 to 3.3 show the hazard calculated for the example

site Braidwood, for the seismicity experts 1, 6 and 12 respectively. These figures show 5 curves. Each one of these 5 curves has been obtained by using only the B.E. ground motion model of the ground motion expert whose index is associated with the curve. Figures 3.4 to 3.6 is the same as above applied to the sample site Millstone. Note that these calculations were made prior to the ground motion feedback meeting, before the model #27 was updated. Since model 27 was chosen as B.E. by expert number 5, we expect the final analysis to provide lower estimates of the hazard as the ones shown here.

Figures 3.7 and 3.8 show the B.E. hazard at the two sample sites, combined over the 5 ground motion experts.

3.3 Other Ground Motion Models impact on the Hazard

In order to analyze the actual effect of every ground motion model on the final hazard, we calculate the hazard by considering the uncertainty on all the parameters of the analysis but in the ground motion model. That is, we fix the choice of a ground motion model and let all other random variable be simulated.

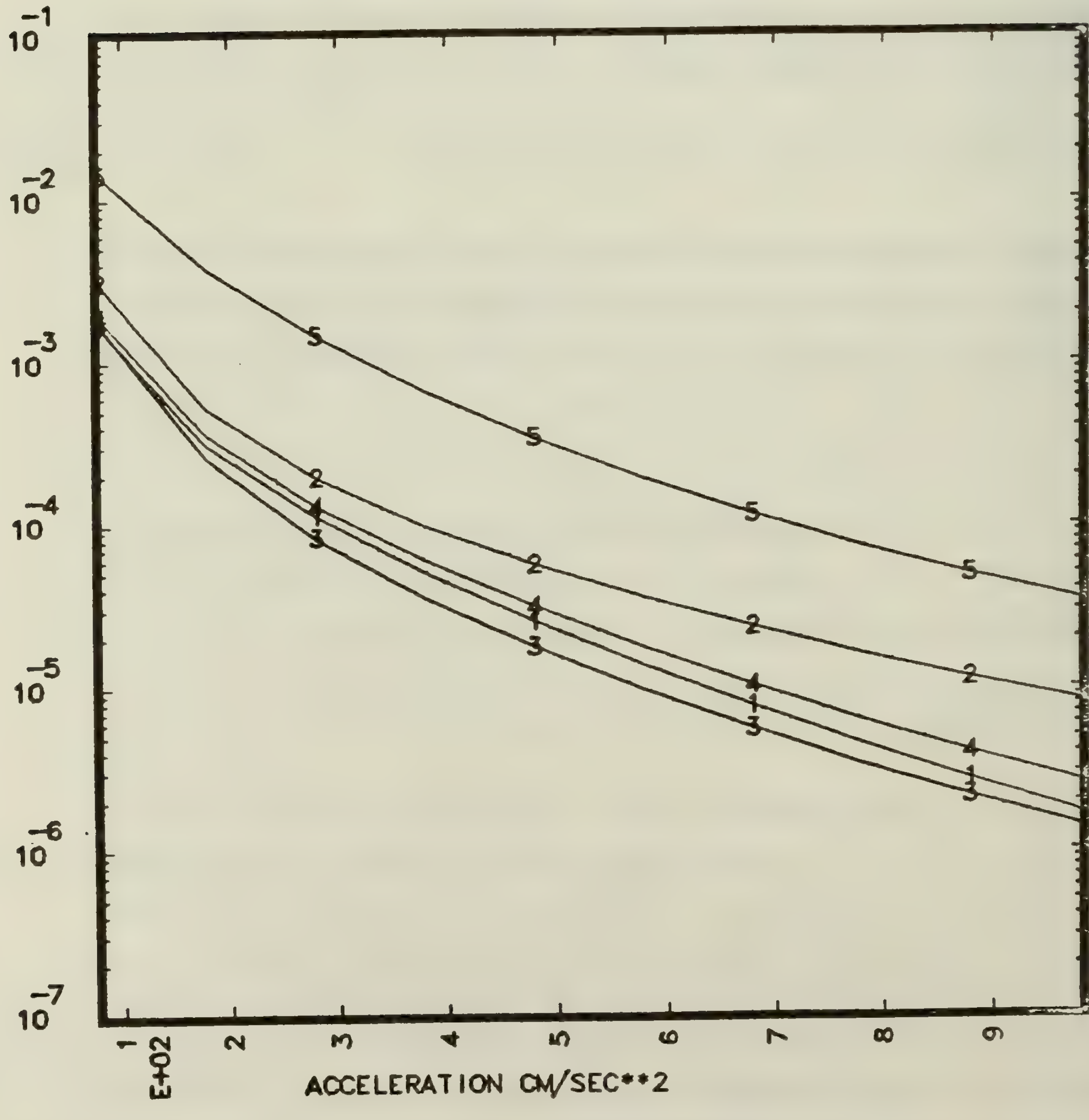
Fig. 3.9 to 3.18 show the 50th percentile hazard curves grouped by ground motion experts. For instance, Fig. 3.9 shows the 50th hazard curve for the six ground motion models selected by ground motion expert 1.

3.4 Case of the hazard in terms of P.S.V. spectra

Because of the added dimension due to the consideration of frequency, only the simplest cases are considered here. The B.E. hazard was calculated at the two sample sites, combined over the three seismicity experts 1, 6 and 12. The Figures 3.19 and 3.20 show the hazard, for the two sites for a 1000 *yr* return period. Each figure includes 3 curves relative to the 3 seismicity experts. No individual calculations, per spectral model, are shown here, but results of such calculations were shown at the meeting. The results of these calculations emphasize the effect of each one of the spectral models on the final hazard.

BEST ESTIMATES FOR SEISMIC EXPERT 1

HAZARD CURVES BY ATTENUATION EXPERT

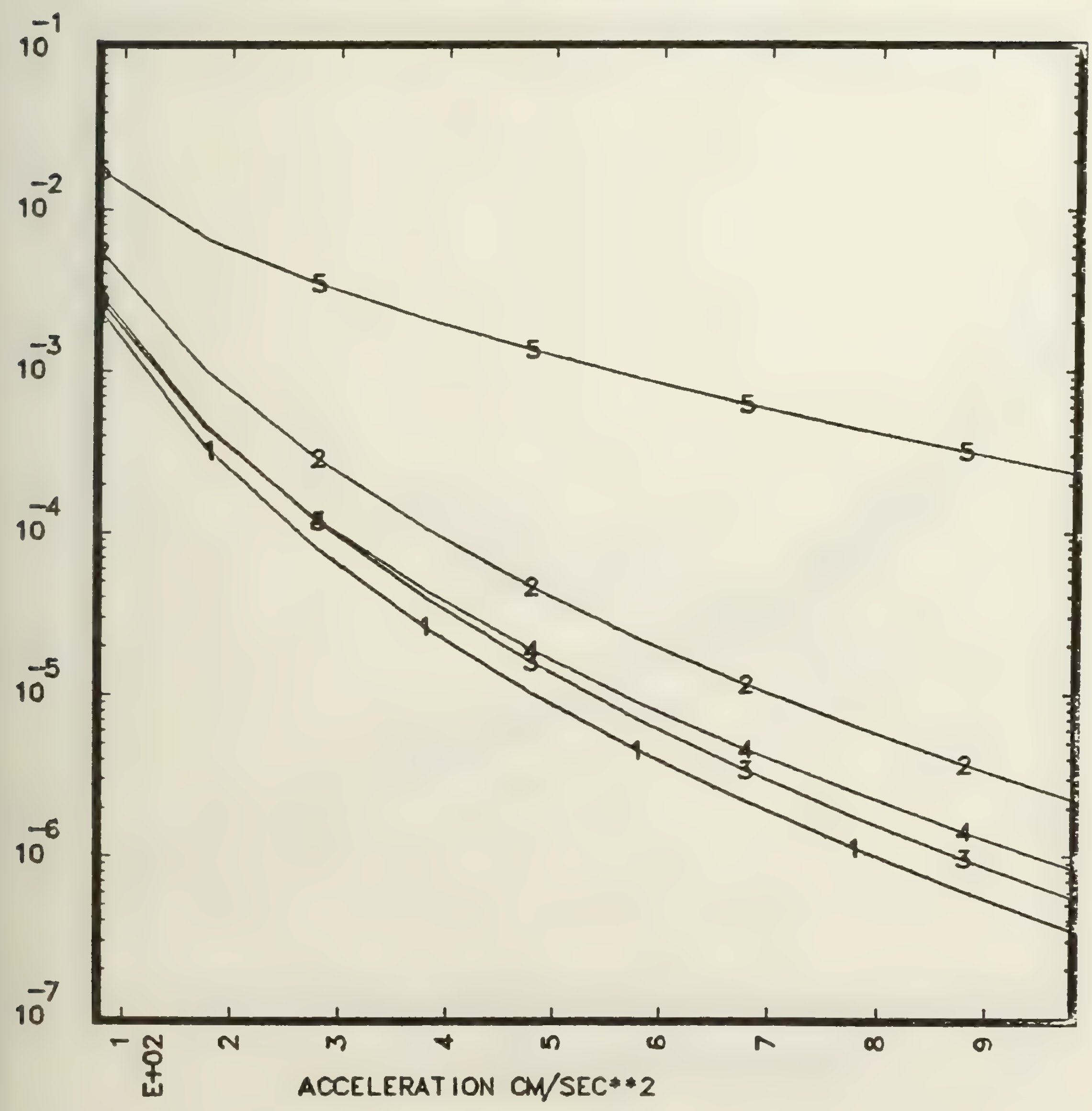


BRAIDWOOD

Fig. 3.1

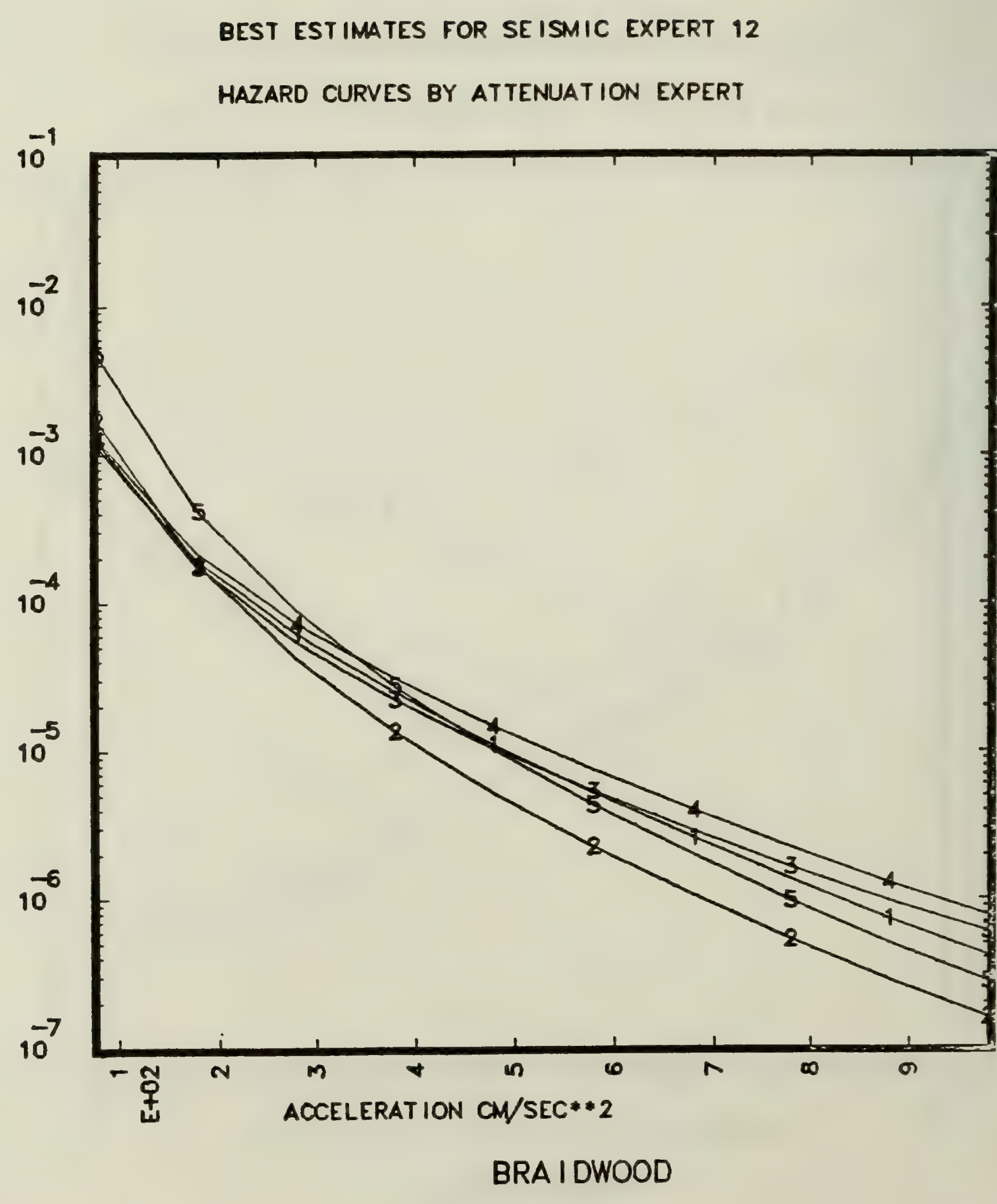
BEST ESTIMATES FOR SEISMIC EXPERT 6

HAZARD CURVES BY ATTENUATION EXPERT



BRAIDWOOD

Fig. 3.2

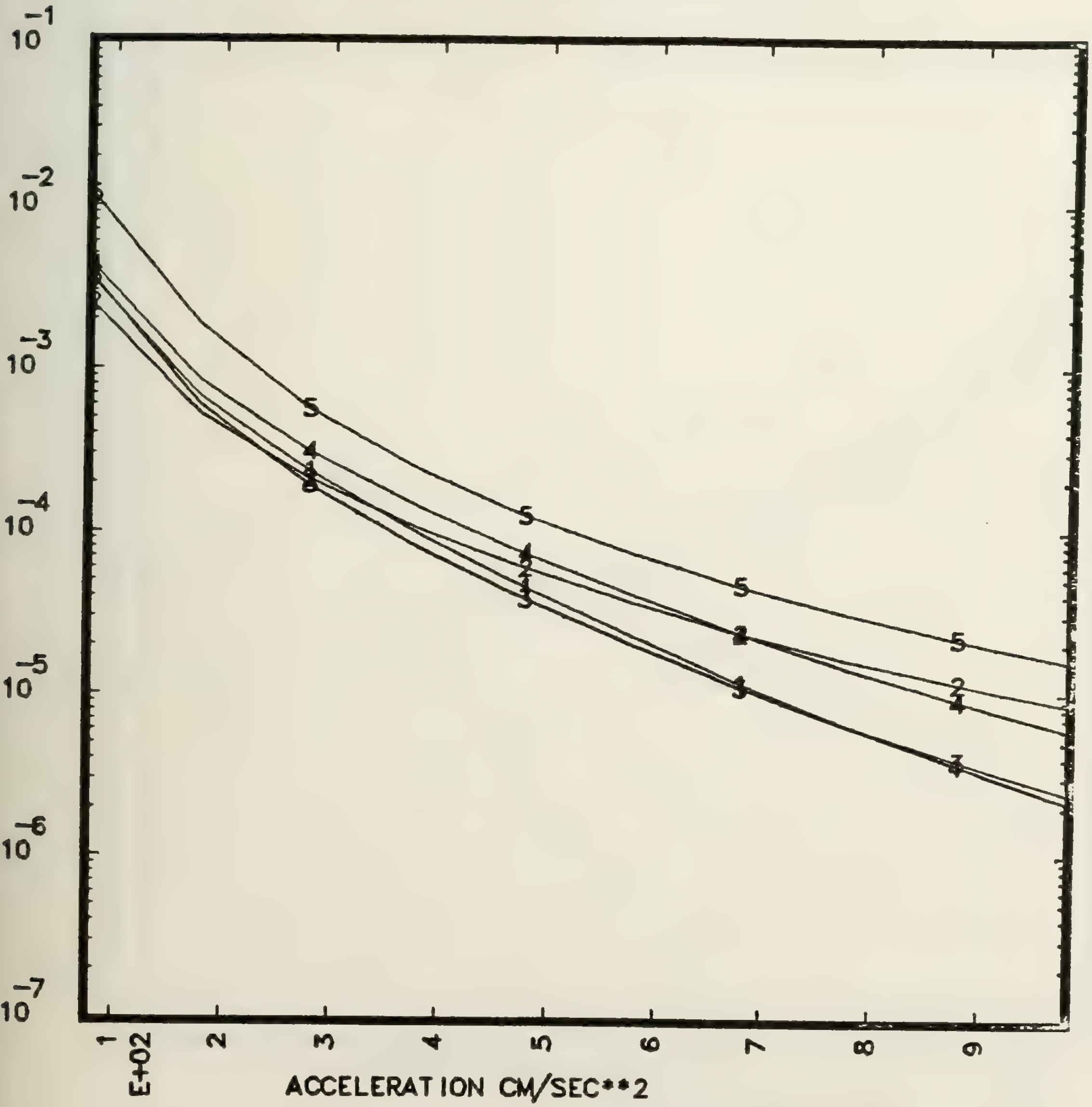


BEST ESTIMATES FOR SEISMIC EXPERT 12
HAZARD CURVES BY ATTENUATION EXPERT
ACCELERATION CM/SEC**2
E+02
BRAIDWOOD

Fig. 3.3

BEST ESTIMATES FOR SEISMIC EXPERT 1

HAZARD CURVES BY ATTENUATION EXPERT



MILLSTONE

Fig. 3.4

BEST ESTIMATES FOR SEISMIC EXPERT 6

HAZARD CURVES BY ATTENUATION EXPERT

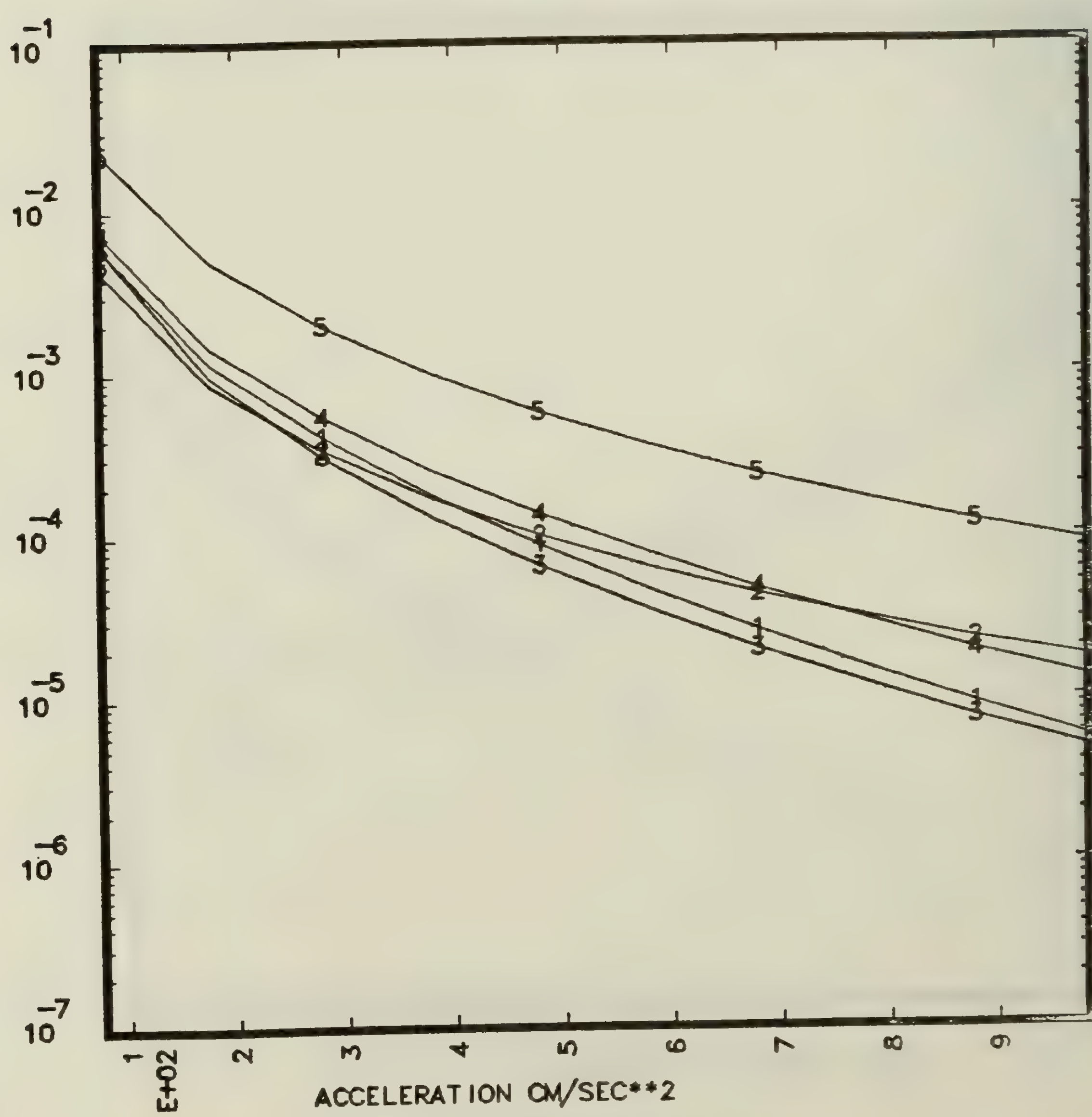


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Fig. 3.5

BEST ESTIMATES FOR SEISMIC EXPERT 12

HAZARD CURVES BY ATTENUATION EXPERT

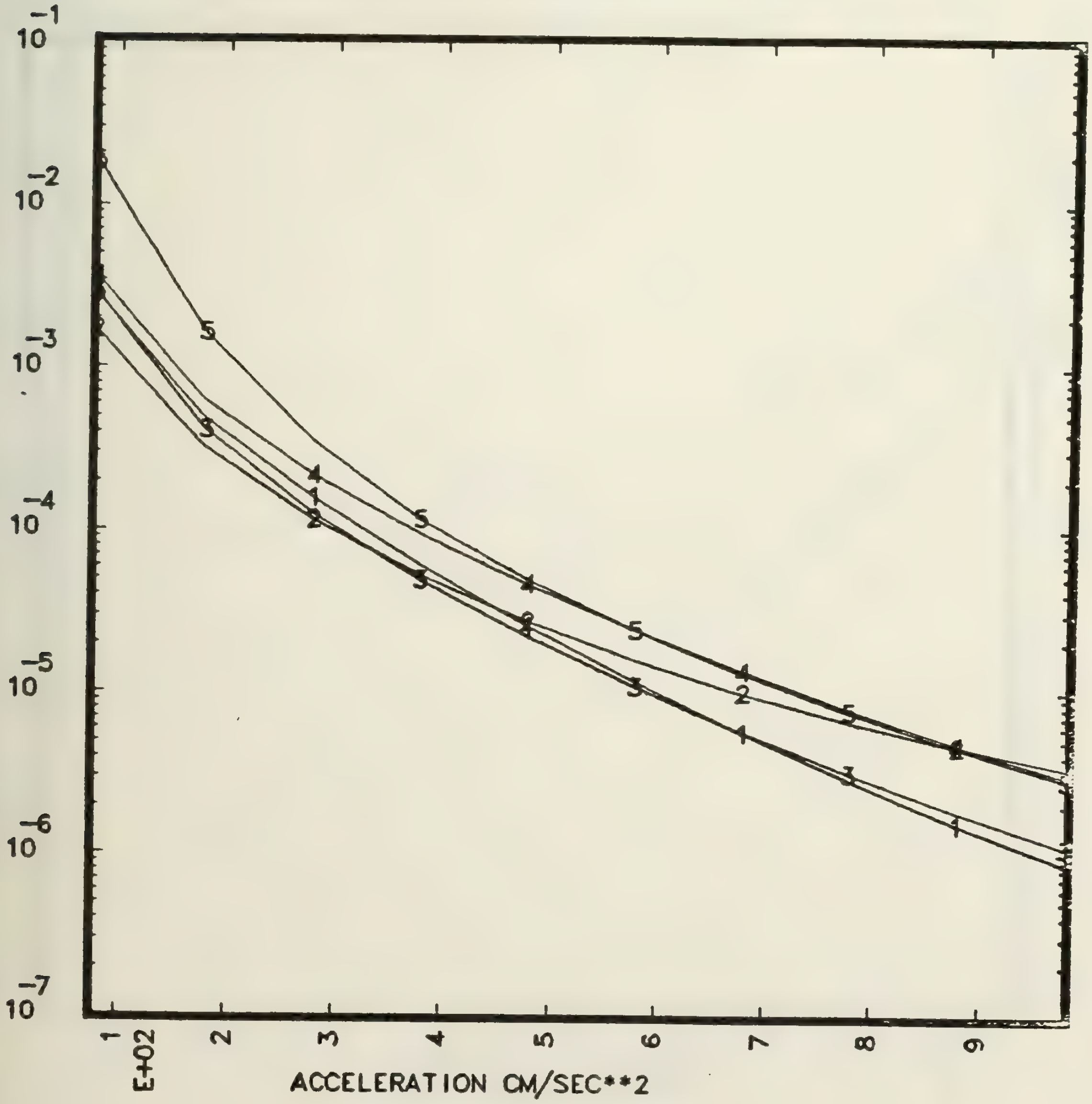

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Fig. 3.6

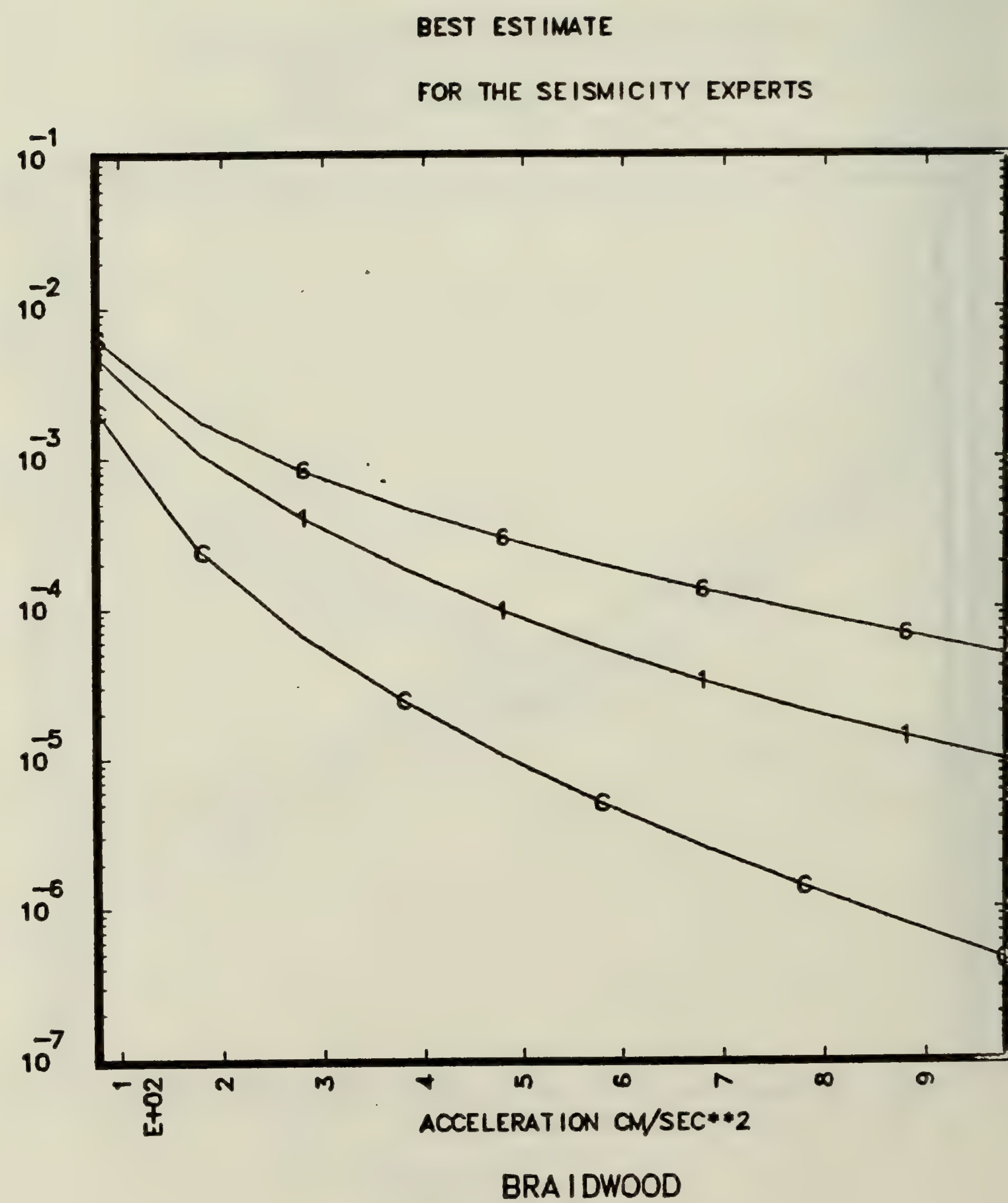


Fig. 3.7 Hazard Combined Over The 5 Ground Motion Experts.

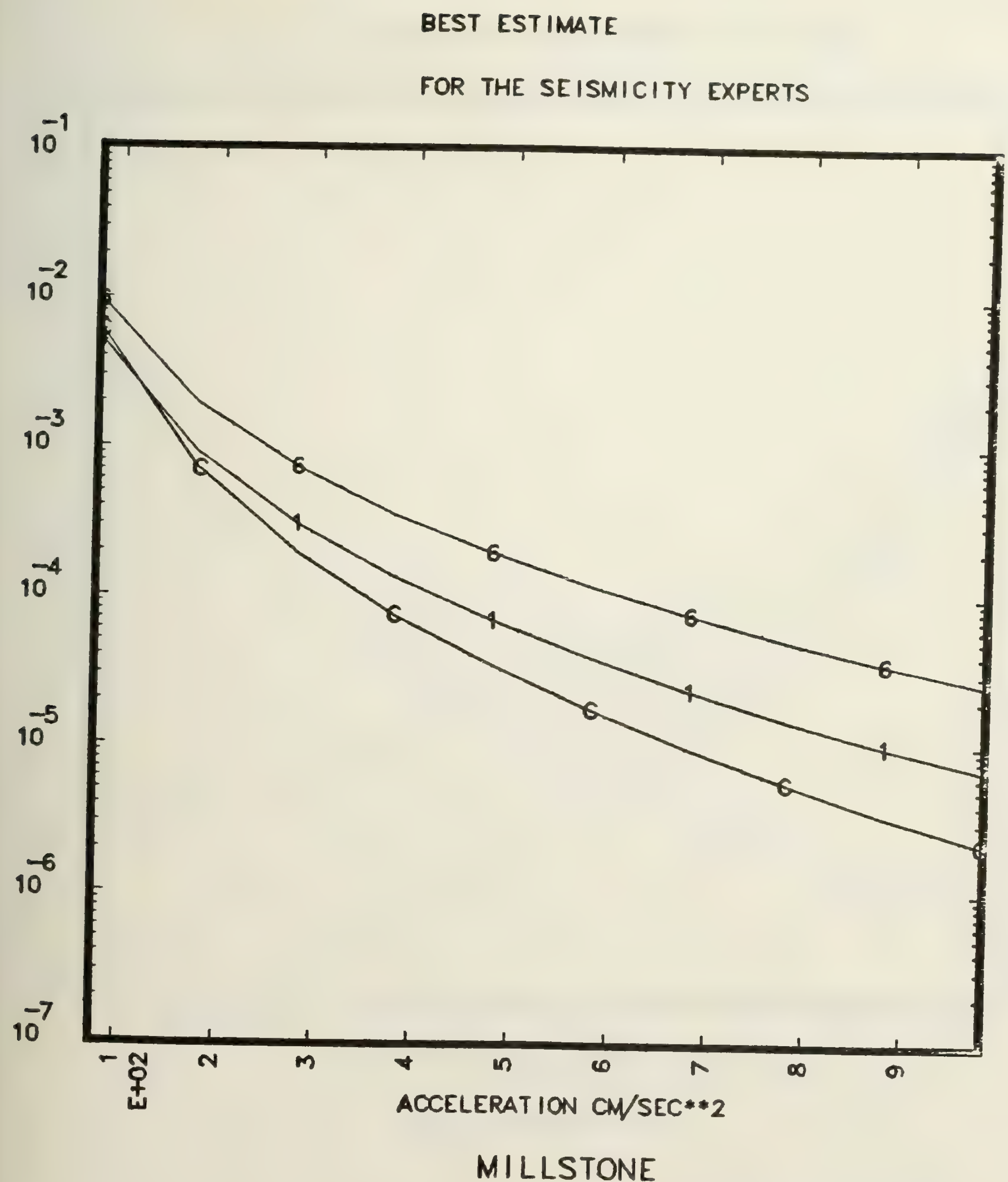
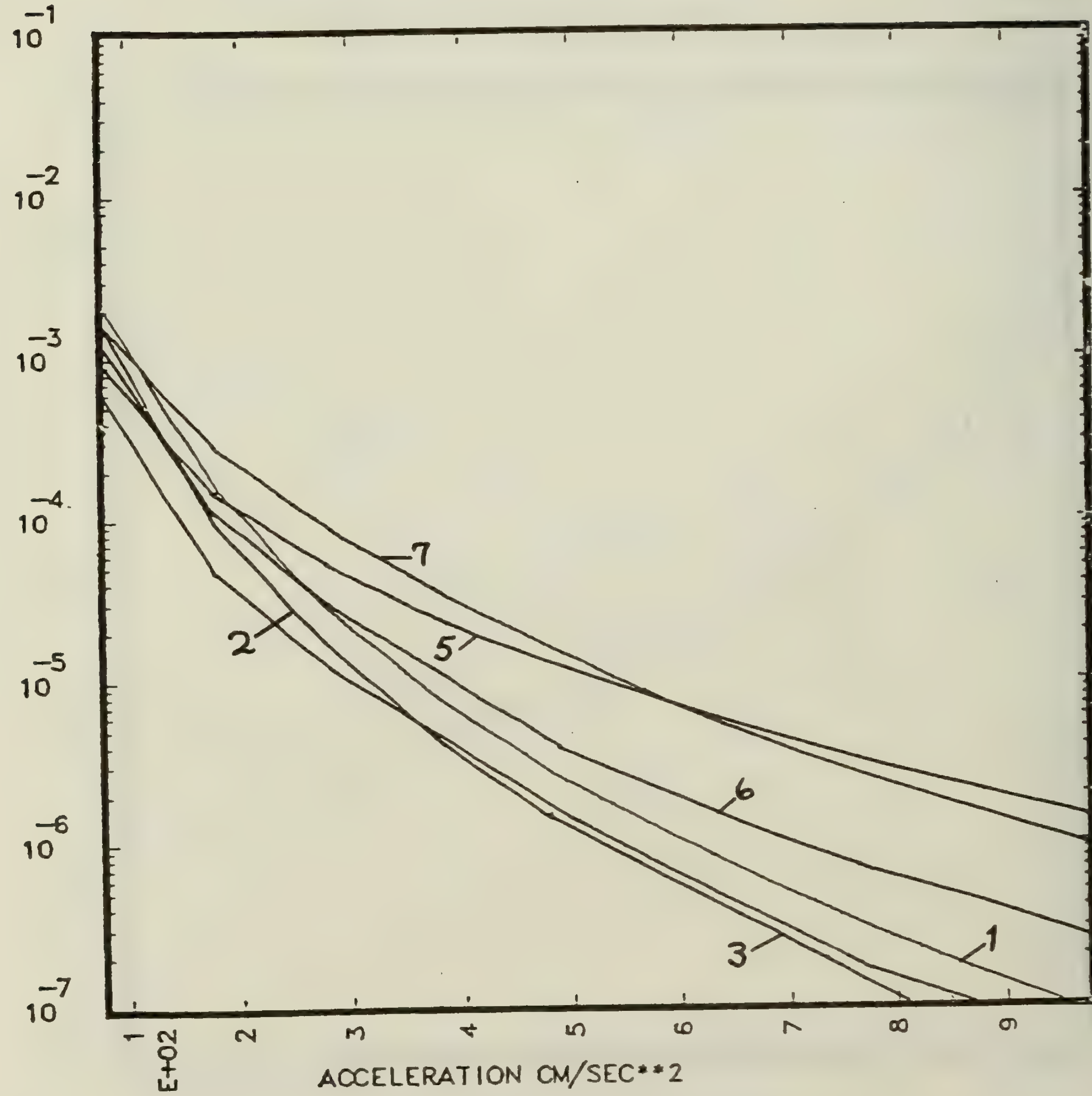


Fig. 3.8 Hazard Combined Over The 5 Ground Motion Experts.

HAZARD CURVE USING ALL EXPERTS



BRAIDWOOD

Fig. 3.9 Hazard Combined Over Seismicity Experts 1,6 and 12, Calculated For Each One Of The Ground Motion Models Selected By Ground Motion Expert 1 (Models 1, 2, 3, 5, 6 And 7).

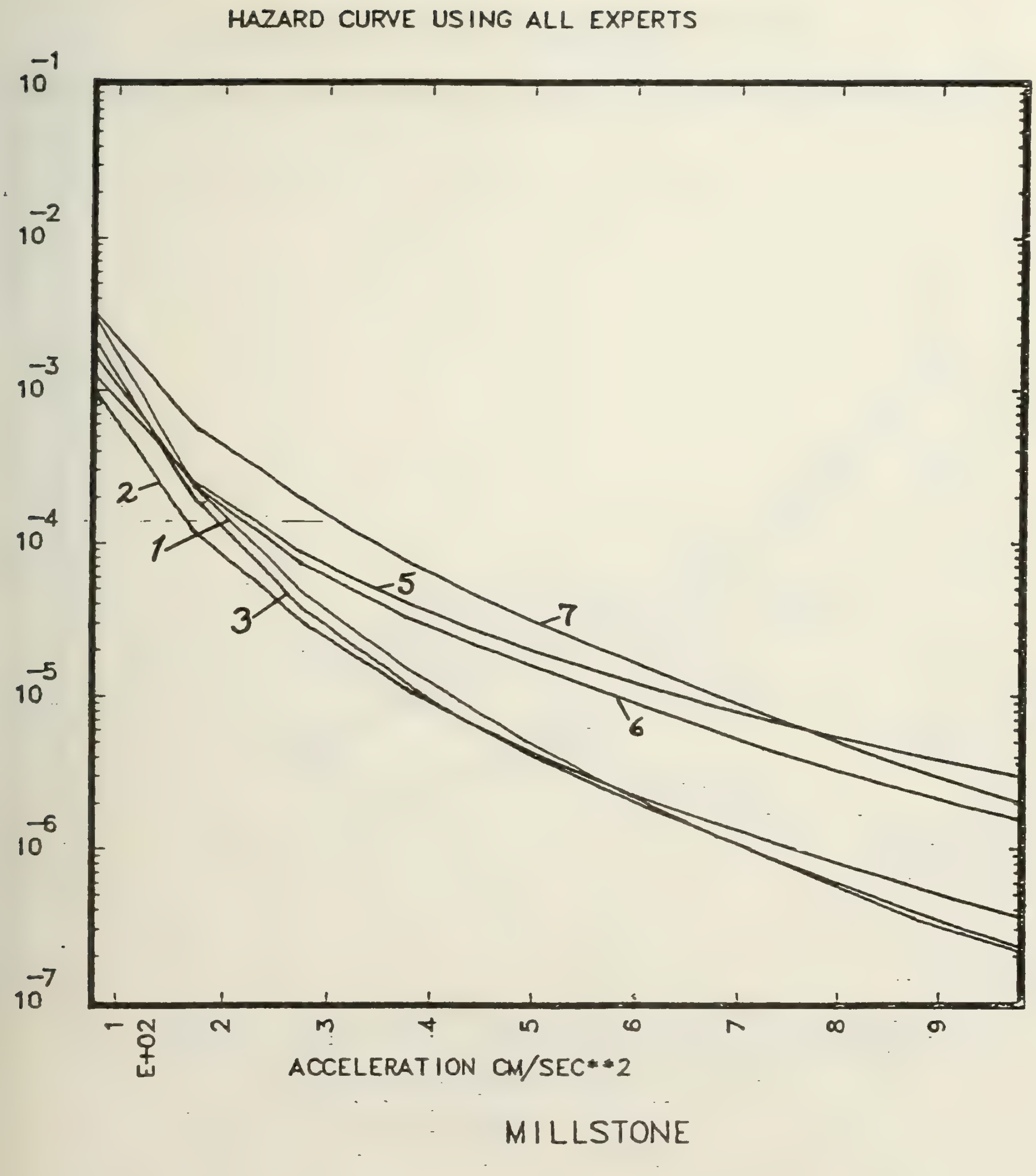


Fig. 3.10 Hazard Combined Over Seismicity Experts 1,6 and 12, Calculated For Each One Of The Ground Motion Models Selected By Ground Motion Expert 1 (Models 1, 2, 3, 5, 6 And 7).

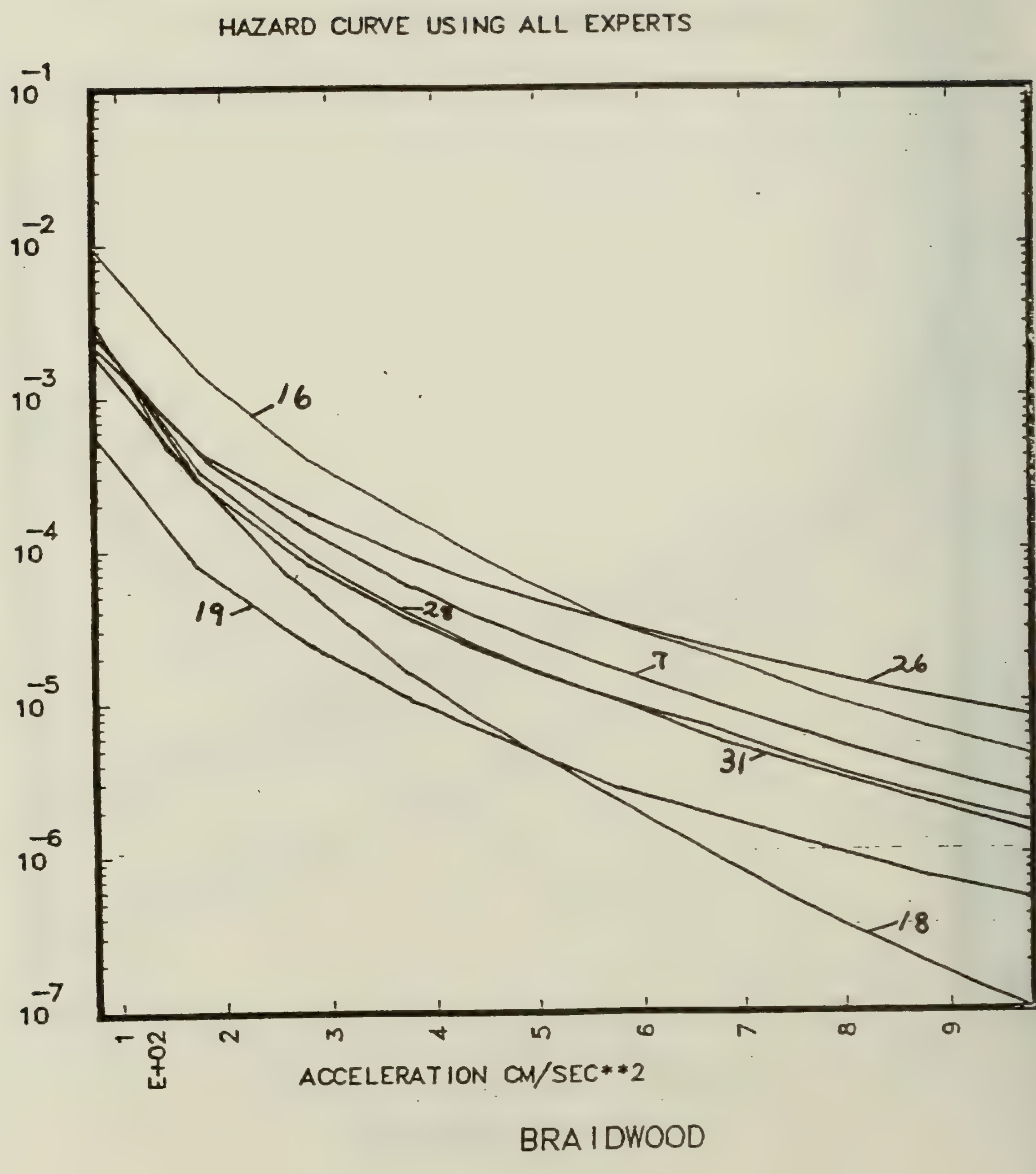


Fig. 3.11 Hazard Combined Over Seismicity Experts 1, 6, And 7, Calculated For Each One Of The Ground Motion Models Selected By Expert 2 (Models 7, 16, 18, 19, 26, 28 And 31).

HAZARD CURVE USING ALL EXPERTS

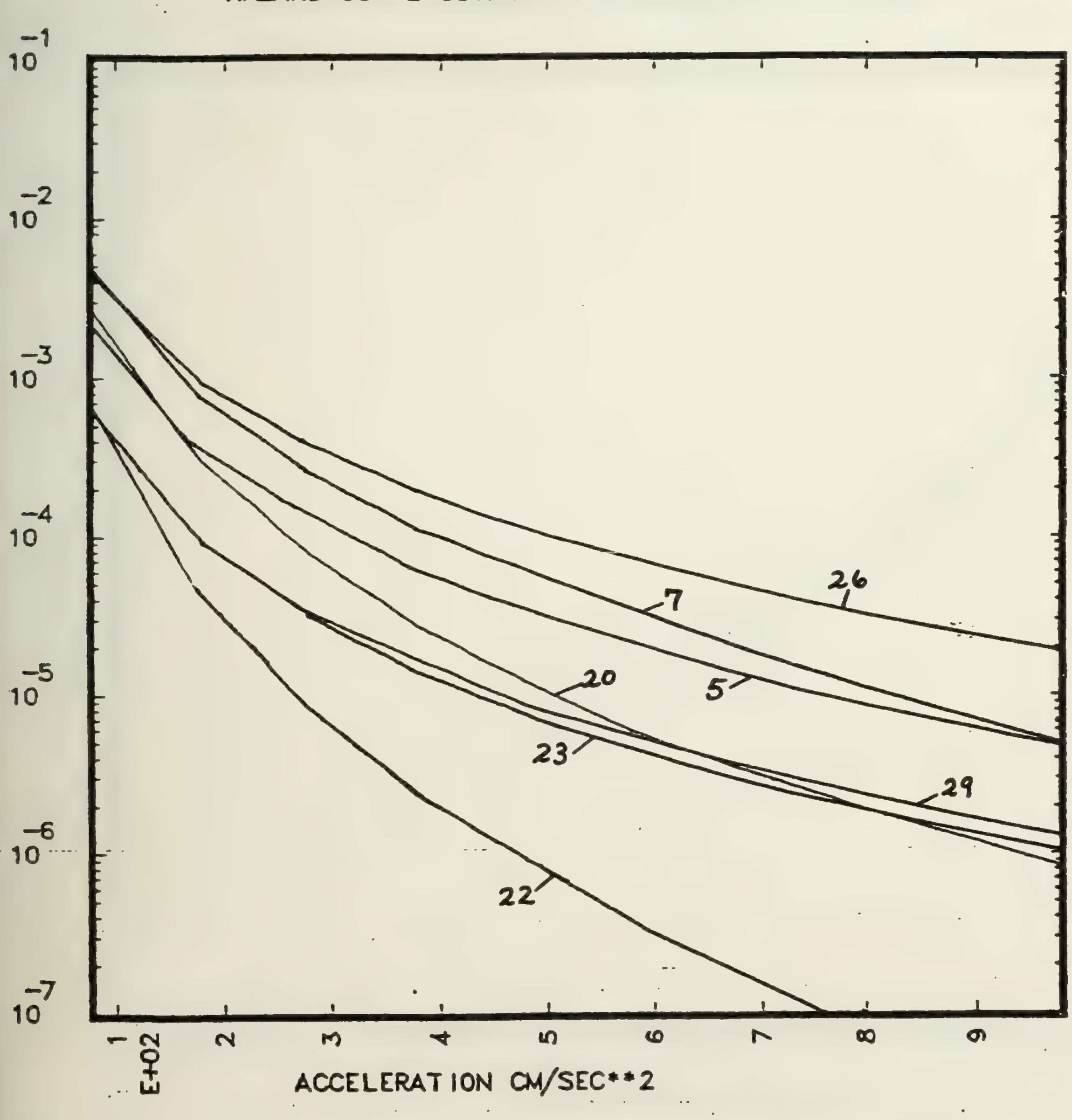


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Fig. 3.12 Hazard Combined Over Seismicity Experts 1, 6, And 7, Calculated For Each One Of The Ground Motion Models Selected By Expert 2 (Models 5, 7, 20, 22, 23, 26 And 29).

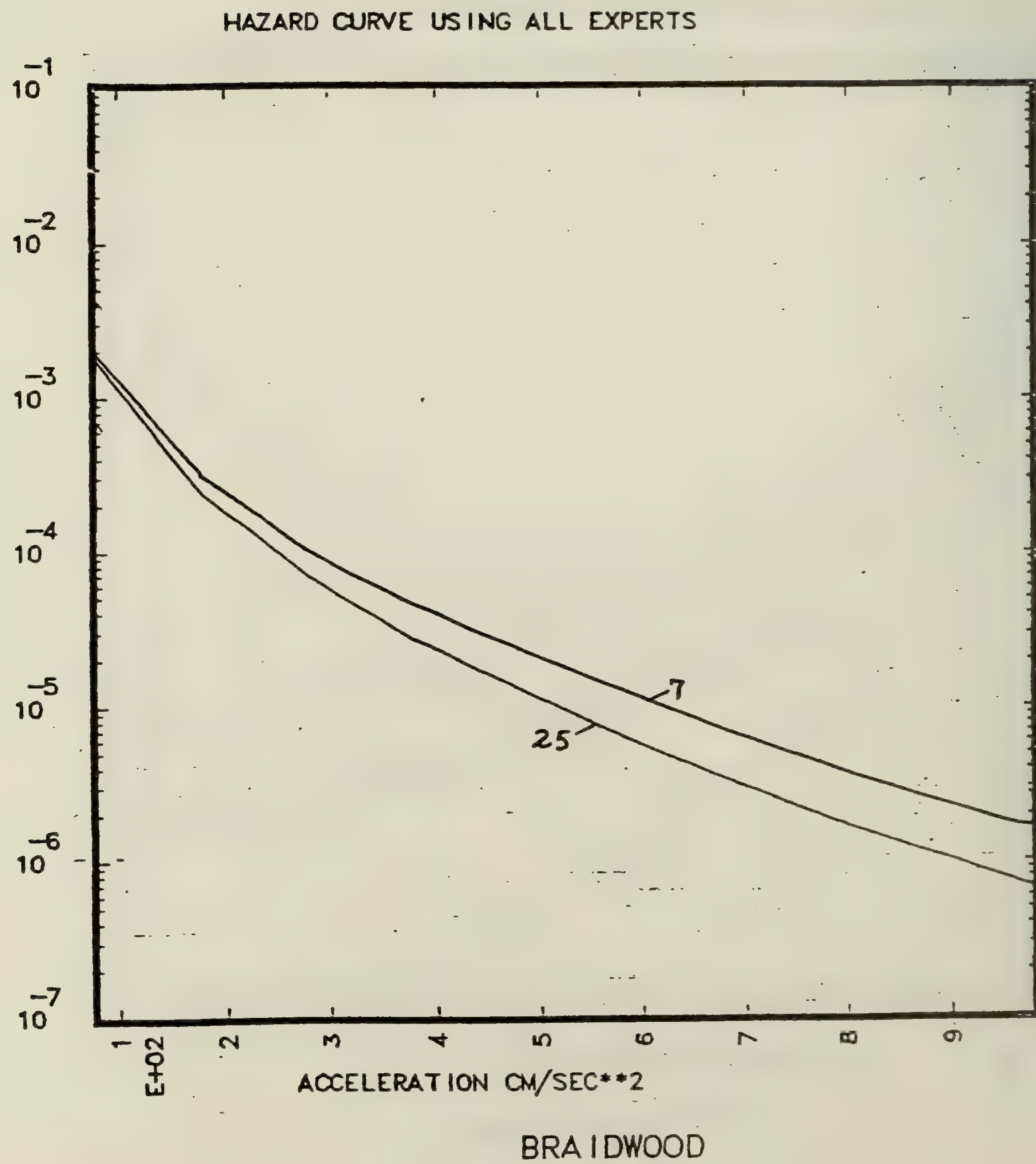

Fig. 3.13 Hazard Combined Over Seismicity Experts 1, 6, And 7, Calculated For Each One Of The Ground Motion Models Selected By Expert 3 (Models 7 And 25).

HAZARD CURVE USING ALL EXPERTS

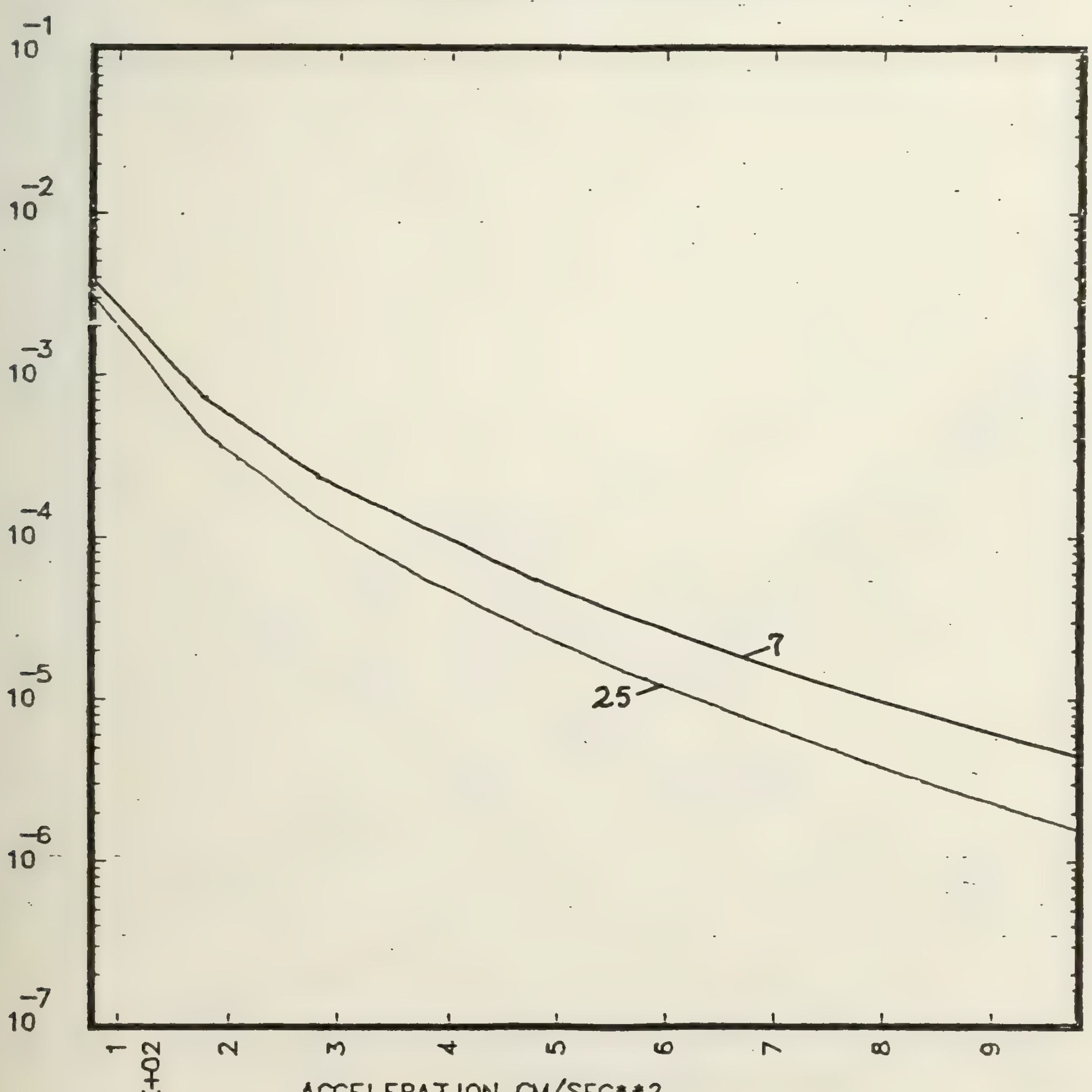

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Fig. 3.14 Hazard Combined Over Seismicity Experts 1, 6, And 7, Calculated For Each One Of The Ground Motion Models Selected By Expert 3 (Models 7 And 25).

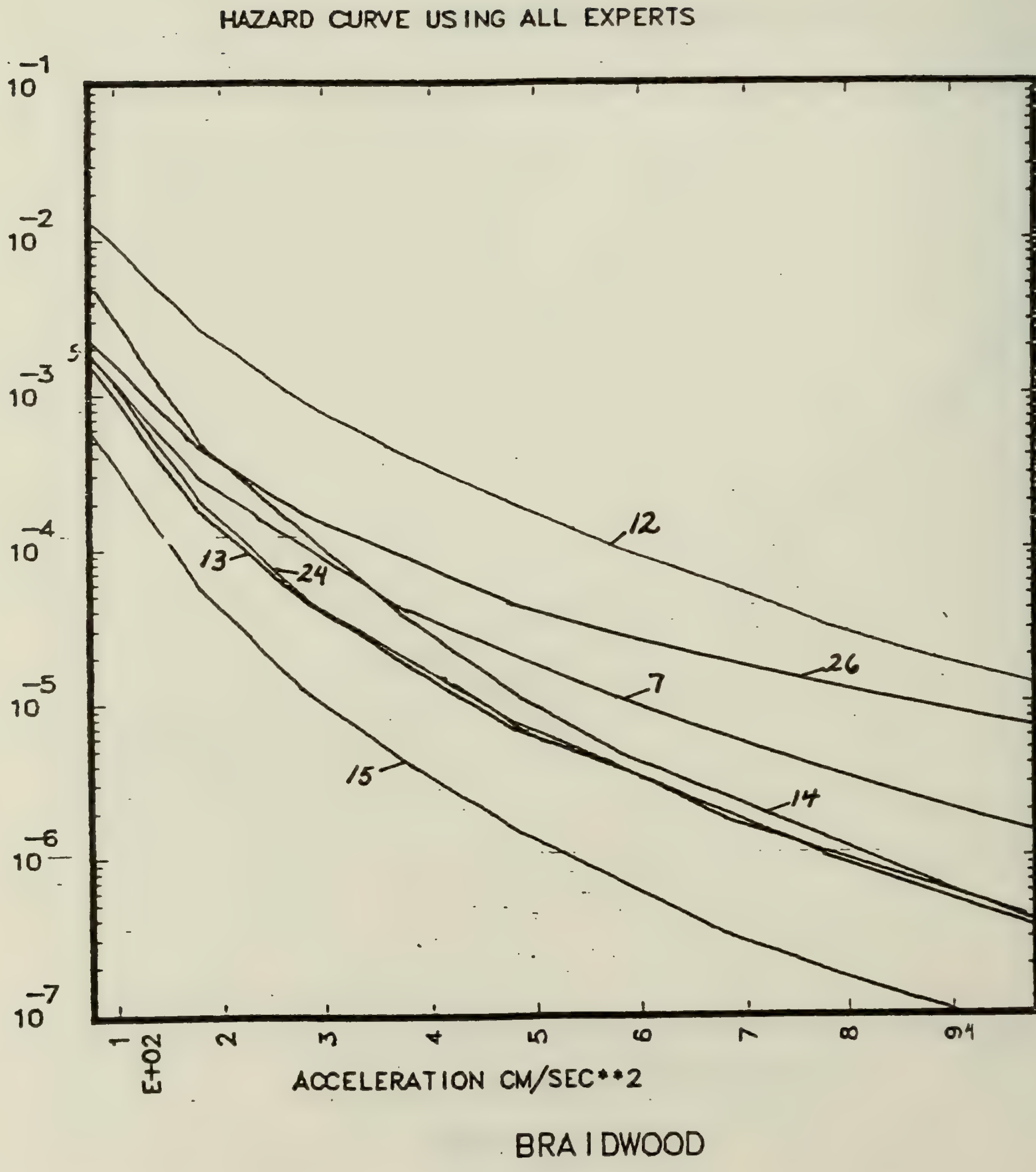


Fig. 3.15 Hazard Combined Over Seismicity Experts 1, 6, And 7, Calculated For Each One Of The Ground Motion Models Selected By Expert 4 (Models 7, 12, 13, 14, 15, 24 And 26).

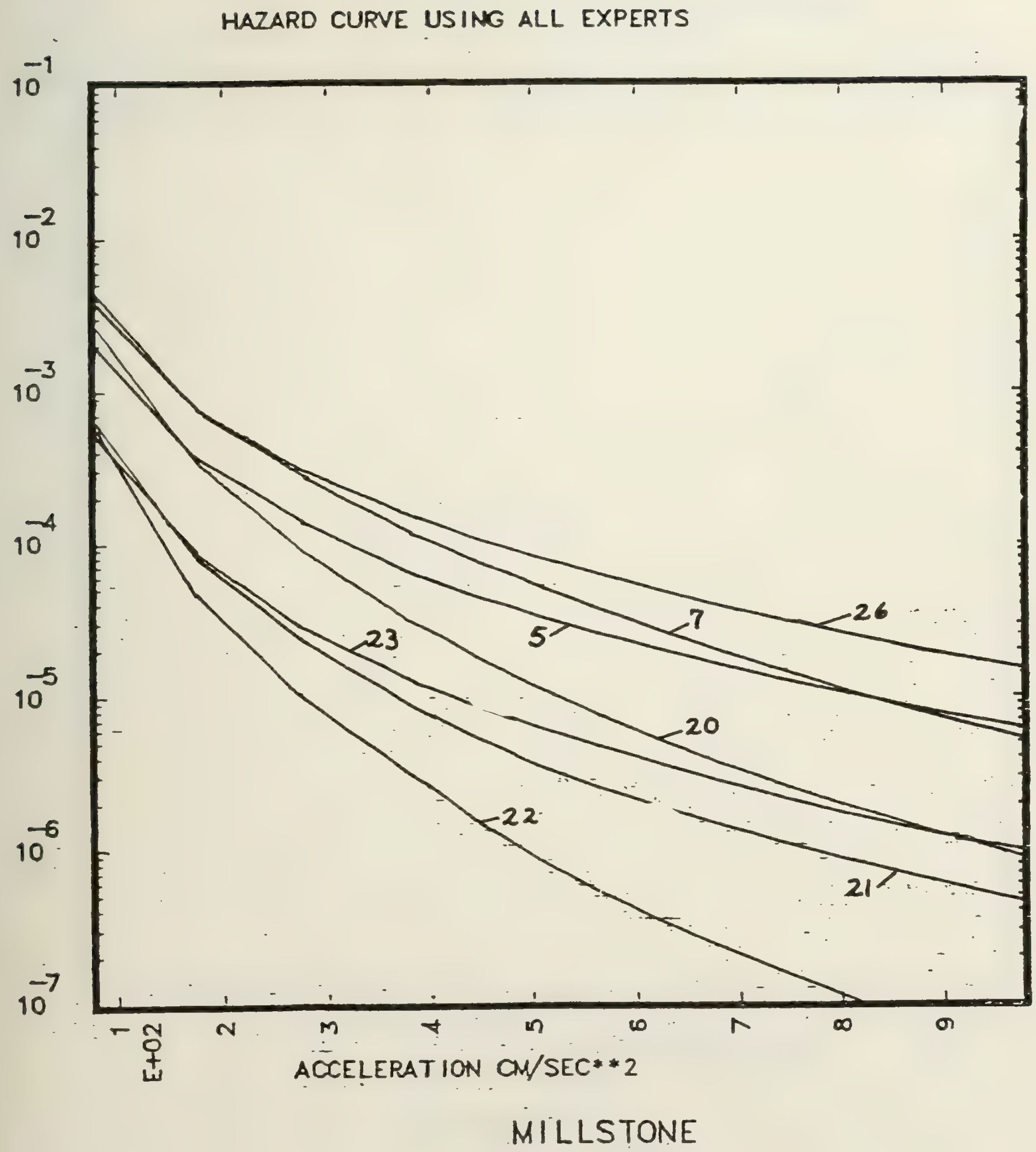


Fig. 3.16 Hazard Combined Over Seismicity Experts 1, 6, And 7, Calculated For Each One Of The Ground Motion Models Selected By Expert 4 (Models 5, 7, 20, 21, 22, 23, And 26).

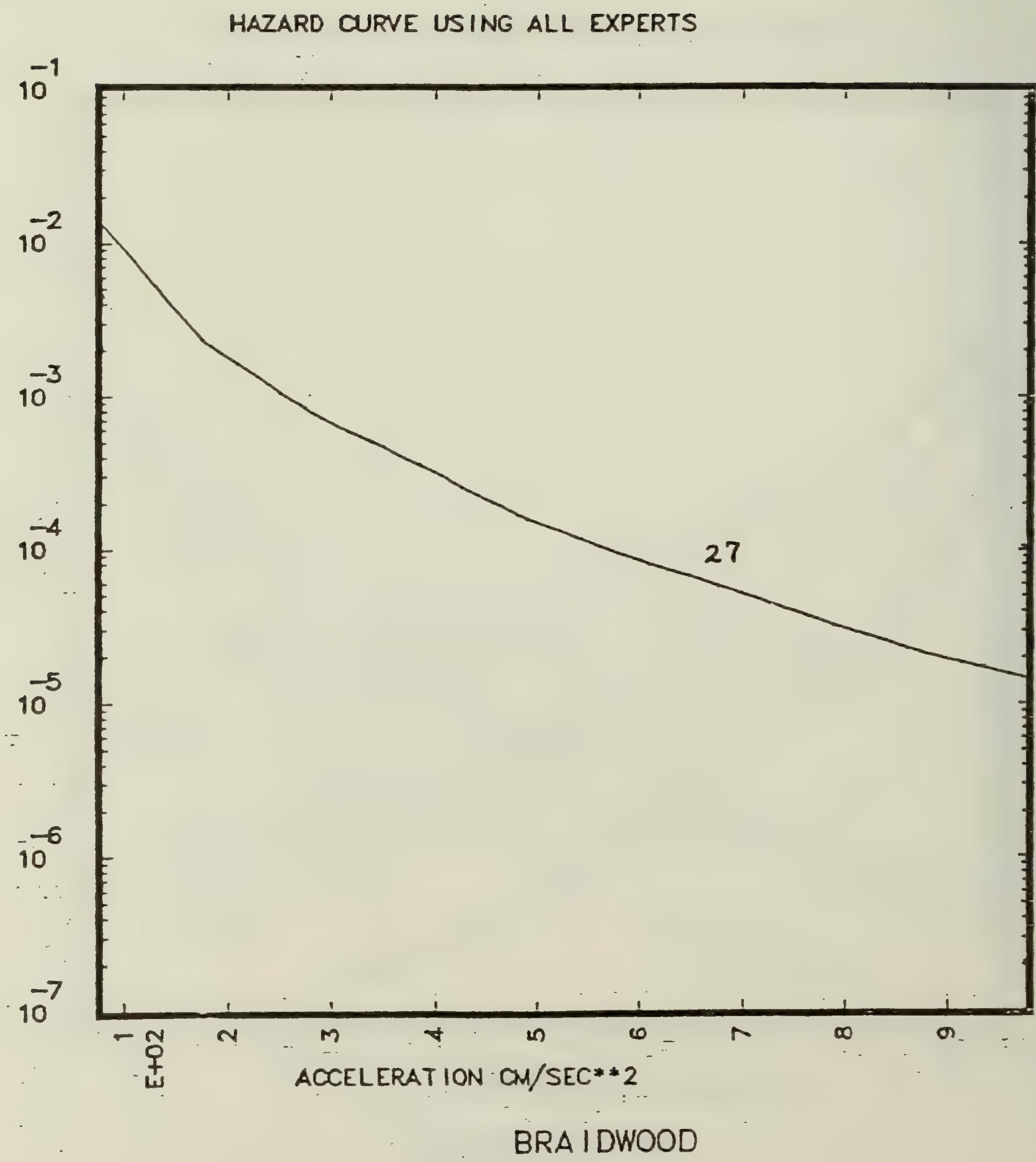


Fig. 3.17 Hazard Combined Over Seismicity Experts 1, 6, And 7, Calculated For Each One Of The Ground Motion Models Selected By Expert 5 (Model 27).

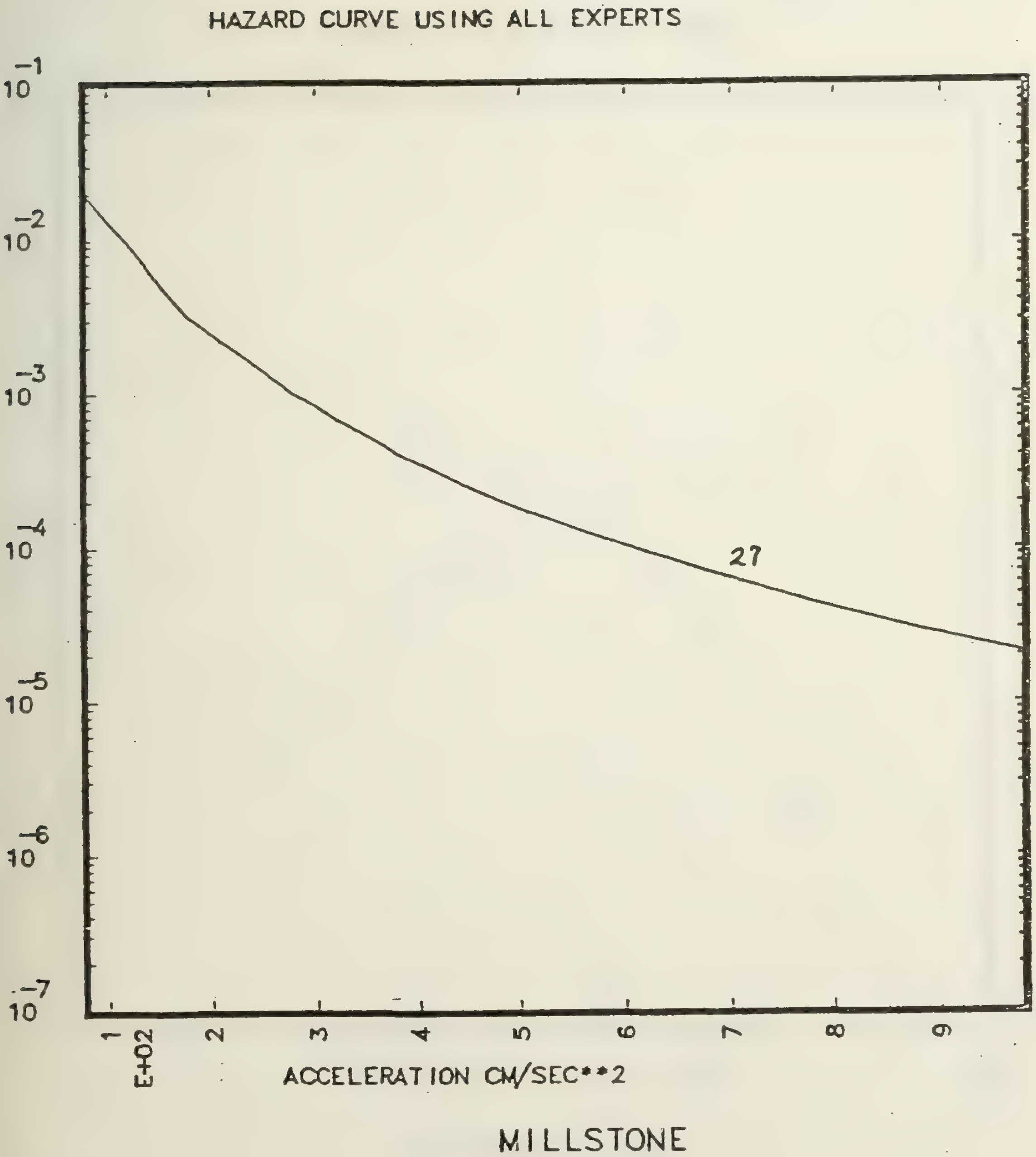


Fig. 3.18 Hazard Combined Over Seismicity Experts 1, 6, And 7, Calculated For Each One Of The Ground Motion Models Selected By Expert 5 (Model 27).

BEST ESTIMATE SPECTRA BY SEISMIC EXPERT FOR

1000. YEARS RETURN PERIOD

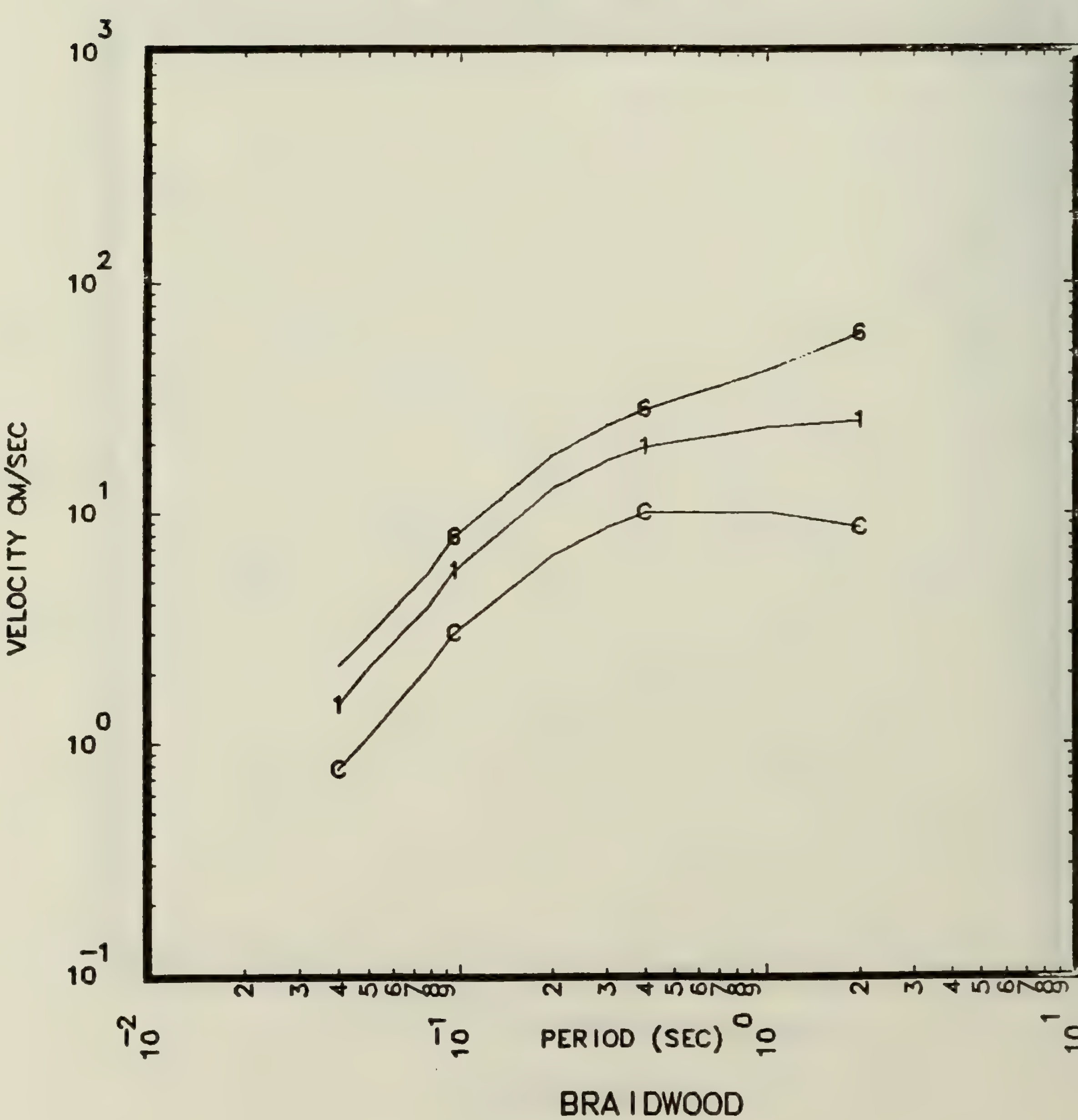
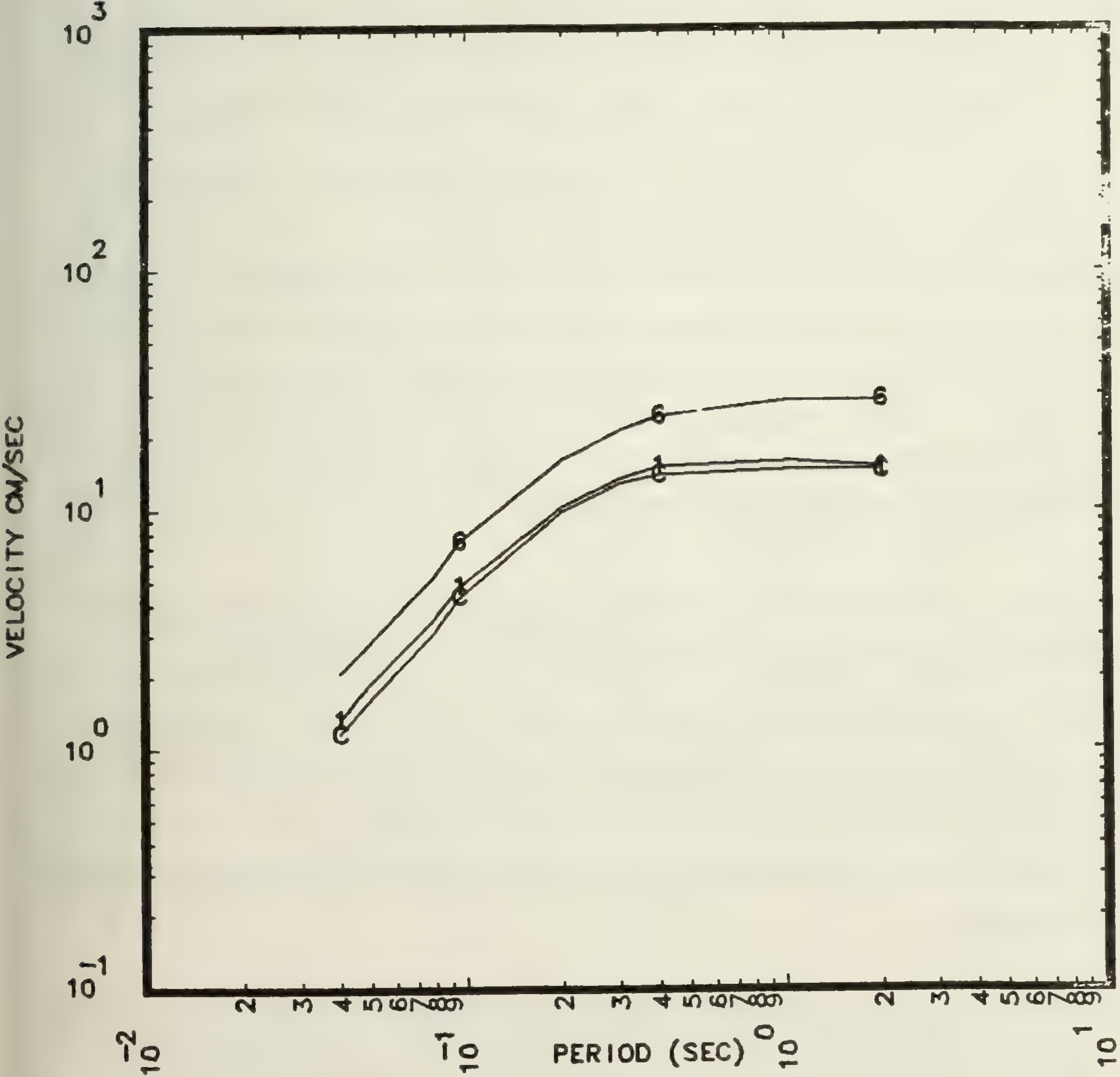


Fig. 3.19

BEST ESTIMATE SPECTRA BY SEISMIC EXPERT FOR

1000. YEARS RETURN PERIOD



MILLSTONE

Fig. 3.20

4. UPPER LIMIT OF THE GROUND MOTION

4.1 Ground Motion Saturation

It was first suggested by Housner (1965) that accelerations in excess of .5g where not possible to occur, but values much larger than .5g have been recorded since 1965. Later Hanks and Johnson (1976) proposed an upper limit of 1.8g for the acceleration. Even if there is no seismological evidence of higher values by actual recording, there is no statistical evidence either to eliminate the possibility of very high strong motion accelerations.

The problem of identification of the upper limit of the ground motion, which we call here ground motion saturation, might also be different in the Eastern U.S. from what is in the West. Since the EUS earthquakes are believed to be richer in high frequencies than the earthquakes in the West, it is legitimate to consider the possibility of occurrence of peak ground accelerations at higher frequencies than for the West. This also leads us to postulate the possible occurrence of peak ground acceleration in the East higher than anything observed in the West.

In spite of these arguments in favor of high saturation values, common sense and basic physics tell us that any GMP cannot be unbounded.

Bounding the GMP seems a logical step for implementation in a hazard analysis, but then we must ask ourselves the following questions.

1) Does it make any difference in a hazard analysis to consdider the GMP bounded?

2) If the saturation value is very high, compared to the mean, does it make any difference in the hazard computed with unbounded GMP?

3) If the GMP is bounded, what is the saturation value?

The most important question is clearly the first one. Many analysts have tried to answer this question, and they concluded that the saturation value of the GMP is a very important value in assesssing the hazard. However, we have to be careful in reaching a conclusion since the saturation values chosen were all in the range of observed values. For example, in a recent study performed by Zemell (1984), it is shown that imposing a saturation value of 1.8g increases the hazard by 50% from what it would be if the saturation value was 1.2g (i.e: .15g vs .10g) for 10,000 yr return period and only approximately 10% (i.e: .065g vs .058g) for 1,000 yr return period. If we were to perform again those analyses with the same ground motion models and same random variation values but with a higher range of saturation values, we believe that the sensitivity of the results to changes in the saturation would be much smaller than in the example cited above.

This last remark leads us to the next question. Let us assume that the saturation value is very high, and let us model the random variation of the GMP by a truncated distribution (such as the truncated lognormal as in our analysis), truncated at the saturation value. Then the difference with using an umbounded distribution would be small since in the unbounded case the probability of exceeding a value equal to the saturation value, would be very small.

In trying to answer the third question above, we have to keep in mind that we are concerned with a frequency range of engineering interest, i.e., frequencies less than 25Hz. This restriction eliminates the peak ground acceleration that we might observe at very high frequencies. In spite of this restriction of the range of values, evaluating the saturation value still remains a very difficult task with a large uncertainty, as no data exist to help us.

4.2 Modeling the Saturation of the GMP

We mentioned above that any estimate of a saturation value would be very unreliable. Rather than trying to associate some uncertainty with the estimate, we prefer to keep this paramenter as a deterministic parameter as we believe that the task of evaluation of a standard deviation would be too unreliable.

We then propose three simple methods of introducing GMP saturation in our analysis, shown in Fig. 4.1:

- o The first method, labeled Type I, assumes that there exists some value a_1 of the GMP which cannot be exceeded at any location. This assumption is guided purely by physical-mechanistic considerations on the resistance of the top layers of soil at site and on the resistance of the rock on the travel path as well as the nature of the earthquak source. This is shown by the Curve C_1 in Fig. 4.1.

- o The second method, labeled Type II, assumes that the upper limit of the GMP is a function of the magnitude and distance from the epicenter of the earthquake. It is more directly based on the observed data and assumes the GMP cannot be greater than the average predicted GMP for a given magnitude and distance, multiplied by a constant factor. Thus, for a given magnitude and a given mean curve, the GMP is bounded by the curve C_2 in Fig. 4.1.

- o The third method relies on both the assumptions made in the Type I and Type II methods. Thus, for a given magnitude and a given mean curve, the GMP is bounded by the curve c_3 which is the lower envelope of the curves c_1 and c_2 in Fig. 4.1.

In Question 6.2 of this questionnaire, you will be asked your opinion on the necessity of considering that the GMP is bounded. If you are of the opinion that it should be bounded, you will be asked to indicate the model of saturation you consider as the best suited for the analysis, and to provide the needed parameters to define your choice of saturation model.

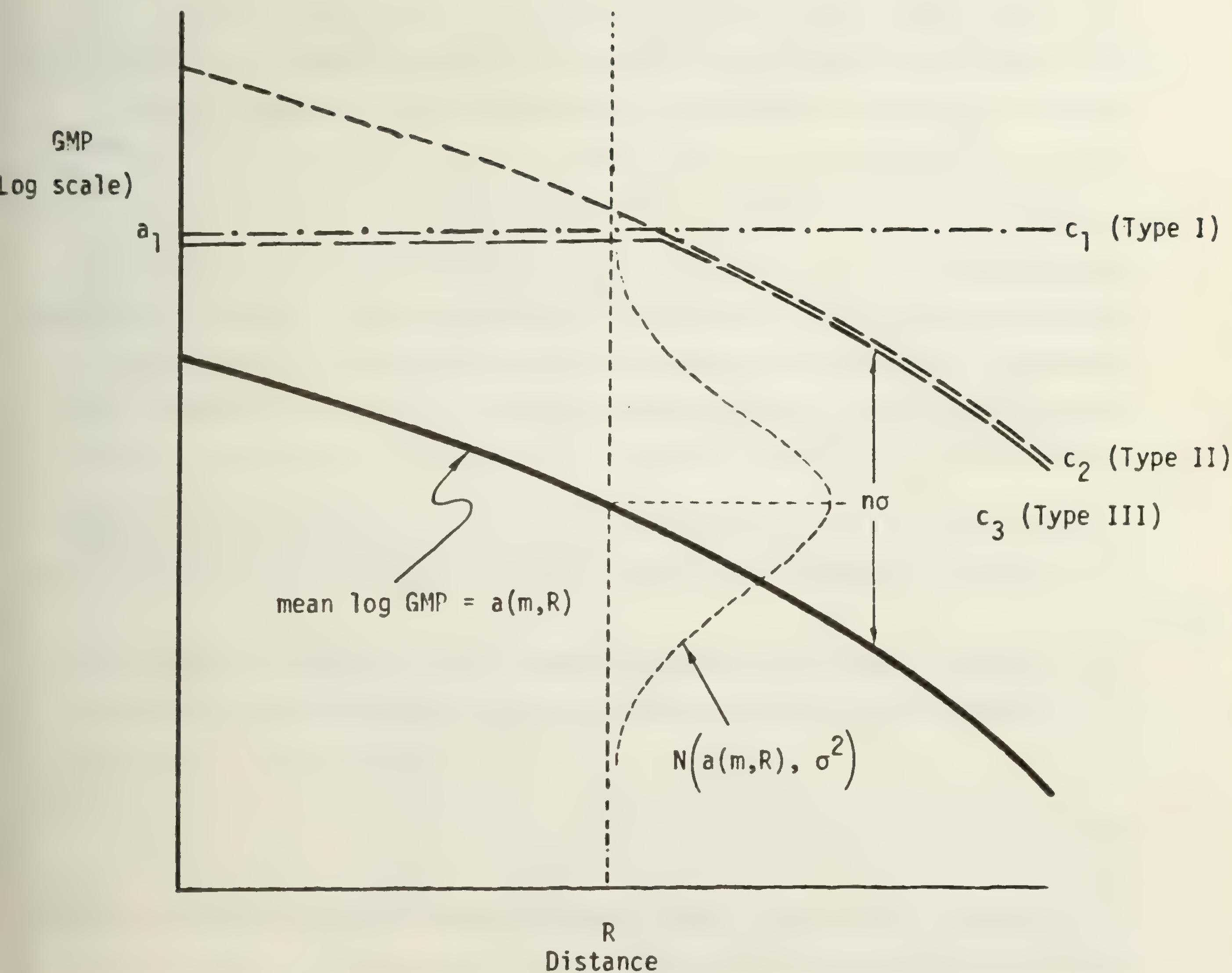


Fig. 4.1 Saturation

Description of the three types of models considered for the physical saturation of the ground motion. The random variation of the logarithm of the GMP is modeled by a normal distribution with mean a(m,R) and standard deviation σ

5. LOCAL SITE EFFECTS

5.1 Background

A possible major deficiency in the hazard curves and uniform hazard spectra presented in the Interim Report lies in the way that the correction for the various sites soil column was incorporated into the analysis. For many ground motion models, e.g., spectral models based on RG 1.60, ATC, or the Newmark-Hall model scaled by Nuttli's velocity model, no correction was entered. For others, only a very simple correction based on use of a simple soil classification procedure such as that introduced by Trifunac and Brady (1975). For example, the spectral model developed as part of the Site Specific Spectra Project (SSSP) was developed using such a simple approach. By this we mean that this ground motion model (the relation between earthquake magnitude, distance and the ground motion at the site of interest) was developed from the set of earthquakes contained in Vol. II of the Cal. Tech. series in the following manner:

1) We separated this data into rock sites and soil sites using our judgment along with reference to the numerous other such division of this data set.

2) Using variations of this data set we developed correlations between the observed ground motion, distance, magnitude and site-type (rock or soil).

Thus, the spectra that we developed are only valid at what we can loosely term average soil or average rock sites.

Trifunac, in his work, used a slightly more complex classification scheme but the basic concept is the same.

The use of such a simple approach could lead to the introduction of significant systematic errors in the analysis. Two major errors can occur:

1) Projected ground motion estimates for a site are based on correlations developed from data obtained at a number of dissimilar sites; hence, there

is little correlation between the spectral peaks from site to site. Thus, the spectral peaks at one site are often averaged with spectral lows for another site. However, a given site may consistently amplify the incoming seismic energy at certain frequency intervals. The net result is that the projected ground motion estimates may be biased on the low side for such a site.

2) The statistic (typically the standard deviation) that measures the dispersion or spread of the data about the mean could be smaller than that for data recorded at different loosely correlated sites.

Our concern about the first possible error is heightened for many EUS sites, because their geological column is significantly different than for the sites making up the WUS. There are typically three major differences between EUS and WUS sites. First, one significant difference is that many EUS sites are underlain by rocks with a higher shear wave velocity (as compared to typical Western U.S. sites). Secondly, many of these sites also share a relatively shallow soil depth varying between 60 and 150 ft. Finally, the soil profile at a number of EUS sites consists of stiff, highly over-consolidated glacial tills which are significantly different than the soil conditions at the sites contained in the WUS data set.

Although our main concern is about site amplification, the value of standard deviation is also of interest because it has a significant effect on the seismic hazard projected for a site.

The ideal way to address these questions would be to develop ground motion models by regression analysis using only data from sites similar to EUS sites. Such an analysis would most likely result in a higher median estimate and possibly in a reduced error term. However, it is not possible to do this because there is so little data from sites with characteristics similar to such EUS sites. A second approach would be to apply correction factors (determined from judgment and analysis such as presented in the following sections) to the uniform hazard spectrum for a given return period.

If correction factors are used, these correction factors (in our opinion) should not be applied to the spectra given in the Interim Report. There are two reasons for this. First, the spectra presented in the Interim Report are the result of combining over a number of different spectral models. These models, for the reasons discussed below in Section 5.3, do not all represent the same base case. The correction factors should be applied in a consistent manner to each ground motion model during the analysis. Secondly, the spectra developed in the Interim Report were computed using an error term for the ground motion model based on data recorded at many different sites. The error is made up of source, travel path, site, and because intensity was used in some cases, building effects. All contribute significantly to the uncertainty. The contribution to the uncertainty due to the data being recorded at different site types and due to role of site intensity should be removed from the estimate of the error term used for the ground motion models in the hazard analysis. The uncertainty in the location of median estimates should be included in the correction factors used.

5.2 The Need for Correction

A reasonable starting point is to address the basic question, is site response an important phenomena that significantly affects the level of strong shaking at ground periods of engineering interest? This question has been frequently adressed in the literature. Most recently, a three day workshop was held at Santa Fe to address this question. One of the papers at this meeting, Rogers et al (1973) noted that the papers at responses to this ranged from "very significant" to "not important in this region" to "important, but impossible to predict." The preponderance of data, however, including damage statistics, intensities, strong motion measurements, and low-level ground motion measurements indicates that site response effects are significant. But there still exists significant controversy as to how important these effects are (given the differences in motions caused by different source mechanisms and different wave-transmission paths) and as to what is the best analytical procedure to evaluate them. The absence of recorded field performance has contributed to the continuing debate on this subject.

It seems that the heart of the problem lies in the difficulty to accurately predict the wave content of a potential earthquake motion. The available procedures are usually based on the assumption of vertically propagating shear (S) waves (1-Dimensional Theory). Many experts in earthquake engineering, however, are unwilling to accept the results of 1-D amplification because, they feel, this theory predicts a greater degree of amplification over a narrow frequency range than is actually observed in nature, except in unusual circumstances. The lack of consipicuous soil effects in the San Fernando 1971 earthquake records has given some support to these arguments, e.g., Crouse (1978). It has also been argued that if soil amplification theories were true, all earthquakes recorded at a site would have very similar frequency content.

On the other hand, the Japanese and Russians have examined numerous case studies showing that the geographic distribution of damage and intensity is in some way related to the thickness and/or other physical properties of the near-surface sediments (Kanai, 1952, Ooba, 1957; Minakami and Sakuma, 1948; Medvedev, 1962). Using recordings of low-level ground motions produced by distant nuclear explosions, Borcherdt and Gibbs (1976) found a high correlation between geographic changes in intensities in the 1906 San Francisco earthquake and geographic changes in mean spectral amplification. This correlation exists up to the highest shaking levels that occurred in that earthquake (Modified Mercalli $\geq$ X). Site effects have recently been isolated in the strong motion data from the 1979 Imperial Valley earthquake (Mueller and others, 1982) and are also observed in the strong motion data recorded during the Fruili and Ancona, Italy earthquakes (Chen et al -- Chiaruttini and Siro, 1981). Analysis of the San Fernando earthquake data set by Rogers and others (1983a) shows that site effects occur at the 28 strong-motion sites they studied. For these sites mean spectral amplification on soil ranged as high as a factor of 5. Data at other Los Angeles sites, employing recordings of Nevada Test Site nuclear explosions, indicated that at some alluvium sites mean spectral amplifications as large as 11 are observed. Many other examples of ground motion studies could be cited that demonstrate the importance of geologic conditions on strong ground shaking.

Appendix B of this report contains a discussion of the reasons why we consider it necessary to include a correction for the local soil column at various sites.

5.3 Proposed Approach

5.3.1 Overview

One of the main objectives of this project is to assess the uncertainty in the estimate of the seismic hazard at selected nuclear power plant sites in the EUS. In keeping with this objective, we want to include the uncertainty introduced by the local site condition at various power plant sites. This uncertainty has both random and systematic components. The systematic component can be accounted for by using several different approaches to obtain the correction factors varying from "no correction" to that obtained by a linear 1-D analysis such as performed in the SHAKE computer program. The random aspect which arises from our uncertainties in the soil column and energy and frequency content of the potential seismic ground motion at the site, can be accounted for by including uncertainty in the correction factors for each systematically different method used to develop the correction factors. Your role as Panel Members will be to select the approaches/correction values you deem best and give subjective weights, i.e., the likelihood that they are correct relative to the other approaches/correction factors.

There are a few important limitations to what is possible, e.g. schedule and budget requirements currently preclude the development of some new approaches. Schedule and budget requirements also restrict what we can do, i.e., acceptable approaches must fit into our analysis scheme. Because of these limitations, our questions in Section 6 are structured into two parts. The first part deals with a limited subset of approaches/correction factors which we can include in an analysis under current schedule and budget limitations. We also solicit your ideas along these lines. We anticipate that at a number of sites the simple approaches/correction factors will have a significant effect on the estimates of the seismic hazard at those sites. Thus, for the longer term we will also suggest/solicit more complex but presumably better ways to incorporate the significance of local site effects into the analysis for NRC's future consideration.

For the short term we propose the following approaches/corrections factors:

1) No correction.

2) Use only a simple soil or rock classification if available -- otherwise, no correction.

3) Develop correction factors for each ground motion model based on several generic site classifications, 1-D analysis data, and judgment.

4) Do a site specific analysis.

5) Other - as proposed by panel members.

Each of these are discussed in detail in the following sections:

5.3.2 No Correction

Here, the argument might be that both our knowledge of EUS ground motion is so poor and the methods we have to assess local site effects so uncertain, that it would be better to do nothing. All site types would be treated the same. Here, it should be noted that some of the ground motion models adopted seem to fall into this category. For example, Nuttli's model #7 makes no reference to site type. One could argue that it is for "generic" soil sties. Certainly, Campbell's models fall into the "generic soil" category as they were developed using only soil data. For other models, e.g. what we have labeled the Trifunac-Anderson model, have a simple site correction term included. If this case is selected and such a ground motion is included, then the value for the site correction term should be specified.

5.3.3 Simple Rock/Soil Correction

For this case, the site types are put into two (rock or soil) or (stiff or soft) or three categories (soft, stiff, basement rock) and a simple constant (for each category) correction factor is applied.

Figure 5.3.1a shows typical correction factors going from soil to rock as a function of period found from WUS data. The curve labeled 1 is based on Joyner-Boore (1982) regression analysis, the curves labeled 2 and 3 are based on Trifunac and Anderson (1977) and the curve labeled 4 is based on the SEP results Bernreuter (1981). For Trifunac's model, curve 2 is between soft alluvium and hard sedimentary rock and curve 3 is between soft alluvium and basement or crystalline rock. Both Joyner-Boore and the SEP use only rock/soil categories.

Figure 5.3.1b is similar to Figure 5.3.1a but now the correction is from rock to soil.

The ratios between Rock/Soil for PGA and PGV are given in Table 5.3.1.

TABLE 5.3.1

Model	Ratio PGA	Ratio PGV
Trifunac (1976a) Basement Rock	1.93	1.07
(Intensity Based) Sedimentary Rock	1.4	1.03
Joyner-Boore (1982)	1.0	0.68
SEP	1.0	0.87
McGuire (1978)	1.22	0.93
Trifunac (1976) Crystalline Rock	0.76	0.55
Sedimentary Rock	0.87	0.74
Campbell (1981)	1.0	---

It can be seen from Table 5.3.1 that there is considerable variation between different studies. These differences arise from several different causes. The first is that form of the model used may not be applicable, i.e., the influence of site type might be a function of magnitude and distance. This is very hard to verify because there are too few sites which are truly rock sites. McGuire (1977) developed a relation between site intensity and the peak ground motion parameters:

$$\ln(a) = \begin{cases} -0.83 + 0.85\ I_s & \text{(medium sites)} \\ 0.27 + 0.6\ I_s & \text{(soft sites)} \end{cases}$$

$$\ln(v) = \begin{cases} -4.02 + 0.95\ I_s & \text{(medium sites)} \\ -1.51 + 0.54\ I_r & \text{(soft sites)} \end{cases}$$

whereas Trifunac (1976) fit the relation

$$\log a = C_1 + C_2\ I_s + C_3 S$$

where S is the site type variable

$$S = \begin{cases} 0 & \text{soft} \\ 1 & \text{sedimentary rocks/stiff} \\ 2 & \text{basement rocks} \end{cases}$$

In the same 1977 study, McGuire also found

$$\ln a = \begin{cases} 1.81 + 0.9\ M_L - 0.9 \ln r & \text{(soft)} \\ 1.47 + 1.0\ M_L - 0.9 \ln r & \text{(stiff)} \end{cases}$$

$$\ln v = \begin{cases} -1.58 + 1.0\ M_L - 0.7 \ln r & \text{(soft)} \\ -3.61 + 1.4\ M_L - 0.8 \ln r & \text{(stiff)} \end{cases}$$

These results would suggest that the use of a simple distance - magnitude independent correction factor might be too simple. It should be noted that in his 1978 paper, McGuire used a simple constant correction factor to account for site conditions in his regression analysis model. He indicates that he did investigate a case where he modeled the site conditions with a relation of the form

$$(C_M M + C_R \ln r)\ ^S$$

where s = 0 for rock sites
    = 1 for soil sites

McGuire concluded that the coefficient C_R was not statistically significant, however, the coefficient C_M was. He noted that the use of a more complex model did not improve the fit to the data, therefore, there was no point in using the more complex model. Unfortunately, McGuire did not report the value of the coefficients C_M and C_R. In addition to possible deficiencies in the form of the mathematical model used for the regression analyses, all of the regression analyses were performed using less than perfect data sets. All the data sets suffer from the use of a poor criteria for the identification of rock sites. Recently, more site boring data has become available to assist in properly sorting the data into categories. The Joyner-Boore (1981) data set is the best in this regard, but it contains a number of questionable sites identified as rock sites. Except for the Joyner-Boore data set records recorded in large buildings and/or in basements, were included in the other data sets used to obtain the results plotted on Figure 5.3.1 and given in Table 5.3.1. Joyner and Boore (1981), Campbell (1981) and (1983) and others have shown that building type and location of the recorder in a sub-basement can have a significant effect on both the PGA and PGV.

The major problem with using the simple category approach is that ground motion models that incorporate such corrections were generally lowly weighted. Only one expert chose such a model as his best estimate model - Model #27 (PGA), #125 (S_V). The other best estimate models, e.g. Nuttli's Model #7 (PGA), #37(V) are based on all data (rocks and soil) or just limited to soil. However, there are so many more data points on soil than rock that effectively the models are "soil" models.

One possible approach would be to introduce a correction factor for these models based on WUS data, i.e., use one of the factors plotted on Figure 5.3.1 to convert from "soil" to rock. This is a somewhat arbitrary approach but would include some correction for the systematic difference that exists between sites. PGA could be corrected using one of the factors from Table 5.3.1. In a somewhat more complex model median, correction factors could be given along with the uncertainty (and a model for the distribution) of the median.

5.3.4 Generic Correction Factors

5.3.4.1 Overview of Approach. The simple model proposed in Section 5.3.3 might be adequate if enough categories are used; however, the data base is too sparse to define many categories. One possible approach, developed in this section, is to supplement the data set with analysis. Our proposed procedure is as follows:

1) Use available soil/rock pairs (soil and rock stations in close proximity to each other that record the same earthquakes) to compute empirically observed amplification factors. This provides a measure of the range of amplification observed and the uncertainty introduced by source, travel path and rheological effects. These results are used to calibrate analytic results.

2) Ideally, one would like to have a sufficient number of soil/rock pairs to put them into a "reasonable" number of categories based on soil type, depth, bedrock shear wave velocity, etc. and develop "generic" median amplification factors (as a function of at least frequency) for each category and the uncertainty associated with each category. Because sufficient data does not exist to even make a "rough cut" at this time, we must resort to analytic modeling. We defined eight categories based on three soil depth categories and two soil type categories plus a rock category and a deep soil category. Two basic soil types were chosen: (1) primarily a sandy type soil column and (2) primarily a "till like" column. Granted, most soil columns are mixed, but defining too many categories becomes pointless and a site specific approach such as discussed in 5.3.5 should be used. Each category contains several different soil columns which are based on actual soil columns at nuclear power plant sites. To incorporate the uncertainty from the source and travel path effects in the analysis, we selected a set of time histories recorded at rock sites with a range of magnitude and distances. These time histories were used as input to the SHAKE computer program and the PGA and amplification factors were computed for each category for each time history. Then for each category, a median amplification factor (correction) and its uncertainty was computed.

One major question arises -- what should these correction factors be applied to? Ideally, we should predict the PGA hazard curve and UHS at each site at a hypothetical unweathered basement rock outcrop and then apply the correction for the appropriate site category to obtain the PGA hazard curve and UHS corrected for local site effects. Unfortunately, it is our judgment that none of the ground motion models available can be considered as predicting the ground motion at an unweathered hard rock outcrop. In fact, the models most highly weighted by the Ground Motion Panel can at best be considered as applicable to only a "generic" soil site. A few of the models chosen can be considered applicable to weathered rock sites. But in our opinion, these models have the serious problem that the different data sets used to develop them have shallow soil sites listed as rock sites and they have data from large buildings/basements intermixed with free-field field data. Also, the set of time histories used to develop the correction factors were generally recorded on highly weathered rock.

Given the lack of data recorded at true rock sites and the possible complexity of the systematic differences between rock and soil sites, it is not clear that even with added analysis that we could develop an acceptable ground motion model for even weathered rock sites. For this reason we included a "generic" soil category in our analyses. Amplification factors were computed relative to the generic soil category as well as rock. Several avenues are possible: (i) Only use the soil version of the various ground motion models and correct using computed correction factors for the site's category. (ii) Use a mixed set; i.e., use the rock version, if available, and use the rock to site category correction factor; otherwise use the soil model and soil to site category correction factor. (iii) Convert all models to a rock version using the approach suggested in Section 5.3.3 and then use the rock to site category correction factor.

5.3.4.2 Selection of Time Histories. Ideally, we would like to have a set of time histories recorded on unweathered hard rock from earthquakes with magnitudes ranging from 4.0 to 7.0 and distances ranging from 2-1/2 km to several hundred kilometers. With such a set, we could rerun our analysis and then examine the results to see if magnitude and distance were important.

Unfortunately, the available set of time histories does not match the ideal set. Most records are recorded on weathered rock -- and in fact, the shear wave velocity of the "rocks" at many sites is closer to a "soil" than a rock. Because only ratios are involved, this may not be a major problem except at hard unweathered rock sites where we do not have a good measure of what the difference might be between the ground motion recorded at hard rock sites as compared to soft weathered rock sites.

Table 5.3.2 gives a list of the records selected. Because of time and budget constraints we have limited our analysis to twenty records using only the maximum horizontal component from each station. We restricted our choice to recordings made either in the free-field or in small buildings. It can be seen from Table 5.3.2 that we have a reasonable distribution of magnitudes but not a very good distribution on distance.

Table 5.3.2

Rock Records Used in the Analysis

Station	Earthquake	Mag. M_L	Dist. R	Accel. g's
Helena Fed. Bld.	Helena, Mont. 10/31/35	6.	8	0.15
Golden Gate Park	Daly City 3/22/57	5.3	8	0.13
Temblor	Parkfield 6/21/67	5.5	11	0.41
Pacolima Dam	San Fernando 2/9/72	6.4	3	1.20
Pacolima Dam	After Shock	5.4	12	0.11
Cal. Tech. Seism. Lab	San Fernando 2/9/72	6.4	18	0.19
Griffith Park Obs.	San Fernando 2/9/72	6.4	17	0.18
Cape Mendocino	Cape Mendocino 6/7/75	5.3	25	0.20
Oroville Seism. Sta.	Oroville 8/1/75	5.7	8	0.11
Gilroy Array No. 1	Coyote Lake 8/6/79	5.9	9	0.13
Gilroy Array No. 6	Coyote Lake 8/6/79	5.9	4	0.42
Superstition Mt.	Imperial Valley 10/15/79	6.6	25	0.21
Cerro Prieto	Imperial Valley 10/15/79	6.6	24	0.17
Superstition Mt.	Westmoreland 4/26/81	5.7	13	0.11
Rocca	Ancona, Italy 6/14/72	4.7	6	0.55
Rocca	Ancona, Italy 6/14/72	4.2	6	0.45
San Rocco	Friuli, Italy 9/15/76	6.1	9	0.12
San Rocco	Friuli, Italy 9/15/76	6.0	19	0.23
Bagnoli	Campunia Lucania 11/23/80	6.7	12	0.18
Sturno	Campania Lucania 11/23/80	6.7	18	0.23

5.3.4.3 Definition of Site Categories

In order to define site categories, site data for more than 60 nuclear power plant sites throughout the United States has been reviewed. Such site data includes geologic profile (layering and depth to rock), soil parameters (soil type, shear wave velocity, compressional wave velocity, density, shear modules and damping ratio at high strain levels) and bedrock properties (shear, compression wave velocity and density). Like most site classification systems, soil depth to the bedrock and soil type are the primary site parameters used to define site categories. Based on our review of the available data from FSAR and PSAR of U.S. nuclear plants sites we have defined the following categories based on the range of the thickness of the soils above bedrock and primary soil type:

Site Class I: Rock Sites. This category includes sites with exposed bedrock including plutonic, igneous, metamorphic, crystalline and sedimentary rock. Sites where the thickness of the soil is less than 25 feet are also assumed to fall in this category and the surface material is neglected as it is generally removed. The mean shear wave velocity from 60 sites is about 6200 fps with a coefficient of variation (COV) of 40%.

Site Class II: Intermediate thickness soil sites. This category includes sites having soil layering thickness ranges from 25 to 300 feet over bedrock. Based on the samples distribution of available sites, we further classify this site class into three subclasses IIa, IIb and IIc.

(IIa): Soil deposit of 25 to 80 feet over rock as shown in Fig. 5.3.2a. The mean shear wave velocity for each site is calculated by weighted sublayer thickness of the site. Among the 12 sites, the mean shear wave velocity is 1500 fps with a COV of 40%. The mean thickness is 48 feet with a COV of 30%. The mean and COV of bedrock shear wave velocity are 6000 fps and 30% respectively.

(IIb): Soil thickness of 80 to 180 feet over rock as shown in Fig. 5.3.2b. The mean and the COV of the shear wave velocity of the 12 sites are 1550 fps and 40% respectively. The mean soil thickness is about 120 feet with a COV of 25%. The mean shear wave velocity of the bedrock is 6400 fps with a COV of 40%.

(IIc): For soil depth of 180 to 300 feet over rock as shown in Fig. 5.3.2c. Only four sites fell into this category. The mean shear wave velocities of soil and rock are 2000 fps and 9350 fps respectively. The mean soil thickness is 250 ft. No COVs were computed due to insufficient site data available to us this time.

Site Class III: Thick soil sites. This is our generic soil category site and includes those sites having soil deposit more than 300 feet over the bedrock. Fig. 5.3.2d shows the shear wave velocity profile for this site class. The mean and COVs of the shear wave velocity among a set of 14 sites are 2115 and 26% respectively. The median value of soil thickness was found 650 feet with a COV of 40%. The mean shear wave velocity is 5700 fps with a COV of 45%.

As these site profiles show a great deal of variability in site parameters, a generic site class can only be defined in a loose manner. For each site class, we only consider two extreme soil types, namely till-like soil and cohesionless soil (sand-like). Since the variation of shear wave velocity with depth for a till-like soil is not significant, a mean constant shear wave velocity was assumed in each site class for the generalized till-like site model for response calculation. However, because the shear modulus for cohesionless soils is more sensitive to the soil depth, it is assumed that the shear modulus varies with the square root of the effective over burden pressure for the sand-like site models.

Table 5.3.3 The means and COVs of the input parameters used for numerical simulation for Site Response Analysis

	Class IIa		Class IIb		Class III	
	Mean	COV	Mean	COV	Mean	COV
H (ft; soil)	48.	0.25	120.	0.25	650.	0.25
Vs (fps; soil)	1500.	0.40	1550.	0.40	2115.	0.40
D (%; soil)	7.	0.60	7.	0.60	7.	0.60
Vs (fps; rock)	6200.	0.40	6200.	0.40	6200.	0.40

For the deep soil site Class III, only a sand-like soil was used, i.e., it was assumed that the shear modulus varied as the square root of the effective over burden stress.

These are rather drastic simpliciations, however, to define too many categories is, in our opinion, pointless and it would be better to go to a site specific analysis. However, this is clearly a point that needs discussion at our meeting and we solict your views. But, we would like to avoid too many categories and it is not clear to us what would be an acceptable set of categories since different layerings are introduced.

5.3.4.4 Analysis Procedure

Basically, the site response was calculated by assuming one-dimensional vertically propagating SH waves. Sites were modeled as a system of horizontal layers of infinite extent. Viscoelastic material model for each layer were assumed -- shear modulus, density, Poisson's ratio, and material damping.

Site response calculation should account for the uncertainty contributed by the variation of depth of the soil model, dynamic soil properties, and the impedance ratio between soil and bedrock. All of these factors could contribute significant uncertainty to calculated response. In addition, the seismic input motions are also an important contributor to the uncertainty. In our analysis to account for the above source of uncertainty, we perform repeated deterministic analysis, each analysis simulating an earthquake occurance. By performing many such analyses and by varying the values of the above input parameters, a mean response and its coefficient of variation can be obtained. The Latin hypercube experimental design (Iman et al, 1980) as used in SSMRP was employed for the response calculation. Variability in the seismic input is included by sampling one of the twenty time histories listed in Table 5.3.2 to obtain a different earthquake time history for each simulation. Variability in the dynamic modeling was introduced by sets of input parameters (mainly shear wave velocities of soil and rock, damping ratio of soil and the depth of soil deposit) from assumed

probability distribution for each simulation. A log normal distribution was assumed for this study. Twenty deterministic analysis were performed for each site class. Thus, to adopt the Latin hypercube sampling techniques, 20 time histories were used. The distribution of each input parameter was then divided into 20 equal - probability intervals. A value was randomly selected from each interval, and the 20 values for each variable were rearranged randomly. The 20 time histories and the permutaded values of the variable parameters were grouped to give 20 combinations of input values for the analysis.

Table 5.3.3 shows the mean and the COV of four key input parameters used in the simulation for site response analysis.

The influence of non-linear soil behavior on site amplification is still an open research area. Currently, very little field data has been obtained to address this question. Tucker and King (1984) show that the observational site amplifications are not much different between groups of strong and weak motions.

Practical non-linear soil constitutive models are not yet available. The non-linear behavior of soil materials cannot be fully described by constant elastic moduli and damping coefficients. However, a good approximation of the effects of soil non-linearities on the response can be obtained by the use of constant strain compatible moduli and damping ratios in a sequence of linear analyses. This method is known as the equivalent linear method (Seed and Idriss, 1969).

Both linear and equivalent linear analyses were performed for site classes IIa, IIb and IIc. The results of our analysis are discussed in the following section.

5.3.4.5 Computed Correction Factors

We noted in Section 5.3.4.1 that the correction factors have to be applied to some reference case -- ideally at an unweathered hard rock outcrop. The correction factor would represent the median value of the ratio of (S_v) site/(S_v) outcrop. However, because many of the ground motion models are only valid for soil, then the correction factor would represent the median value of ratio of (S_v) site/$(S_v)_{III}$ where $(S_v)_{III}$ is the base-case Class III defined above.

Our analysis of both actual data and from computer modeling indicates that there is considerable variability in this ratio from earthquake to earthquake. The variability can reasily be accounted for by including it in the simulation process. The main problem, in our opinion, is in defining the ground motion levels and frequency content for the base case. The difficulties in defining the base case are threefold: (1) few (possibly none) of the ground motion models are applicable for rock sites; (2) what soil column would represent the generic soil models and; (3) the set of rock records contain many records obtained at soft weathered sites.

As a starting point we have taken the "generic soil site" to be represented by a deep sand-like (shear-wave velocity a function of the depth) site with linear visco-elastic properties, i.e. site Class III defined in Section 5.3.4.3. We have examined two sets of correction factors -- one set relative to the rock outcrop records and one set relative to the Class III generic soil sites. The spectra at the surface of the Class III sites were computed using the set of rock time histories given in Table 5.3.2 and for twenty sets of soil column properties obtained by simulation using the approach discussed in Section 5.3.4.4.

Because it is conceptually the simplest, we first summarize the results relative to "rock"; i.e., relative to the set of time histories/spectra given in Table 5.3.2.

Figure 5.3.3a shows a comparison of the median amplification factors relative to the rock site category computed for sand-like sites for categories IIa (25'-80'), IIb (80'-180'), IIc (80'-300') and III (deep). Also shown are the amplification factors computed by Joyner-Boore (1982). The match between Category III and Joyner and Boore's results is better than one might expect. It is interesting to note that our modeling results indicate that the peak acceleration amplification factors is unity in agreement with the results obtained by Joyner and Boore and Campbell. There is considerable departure at longer periods (greater than 1.5 seconds). This might be due, in part, to the fact that some of the rock records were not all base line corrected so that there is some longer period noise in the rock records. Part of the departure might be due to the fact that the damping is not a function of frequency; hence, the long period motion has the same damping as the short period high frequency motion.

There is considerable uncertainty associated with the median curve for each category. For example, Figure 5.3.3b shows the envelope amplification factors, the median and 1-Sigma amplification factors for Category IIb and Figure 5.3.3c for Category III.

Figure 5.3.4 shows a comparison of the median amplification factors relative to the rock outcrop category for till-like sites for categories IIa, IIb and IIc. The amplificastion factors relative to the rock outcrop category for Category III sites is also shown. Comparison of Figure 5.3.3a and 5.3.4 show that the till-like categories have somewhat lower amplification than sand-like categories.

We have made an initial set of runs using the equivalent linear model. Only a sample of these results are shown in Figure 5.3.5. Figure 5.3.5a shows a comparison between the amplification factors for sand-like Category IIb obtained using the records in Table 5.3.2 as recorded, all scaled to 0.2g and all scaled to 0.4g. There are only minor differences between the different cases. Figure 5.3.5b shows the envelope, median and 1-Sigma amplification curves for the set of records in Table 5.3.2 and Figure 5.3.5c shows the same results for the case when all the records were scaled to 0.4g. It is seen by

comparing Figs. 5.3.5b & c that the uncertainty is approximately the same. Our sensitivity analysis indicates that the damping of the soil is one of the most important parameters. We considered three cases for damping of the soil:

1) Median damping value of 2% with COV of 40%.

2) Median damping value of 7% with a COV of 40%.

3) Equivalent linear core with a best estimate curve based on available data.

Figure 5.3.6 illustrates the importance of damping for IIb sand like soils by comparing the three damping cases. Comparison of Fig. 5.3.6 with 5.3.5a shows that the choice of the damping parameter's value has an important effect on the computed amplification factor.

If Figs. 5.3.3a and 5.3.4 are compared to Figs. A-5, A-7, A-14, A-15, A-16, A-28 in Appendix B it is seen that the computed amplification factors have a shape similar to those observed at actual sites, but are somewhat lower. This, in part, could be due to the fact that each site category covers a relatively wide range of sites and, in part, because layering was not considered. Layering can increase the amplification because layers with large contrasts in impedances can occur. This point is discussed below in Section 5.4.

As noted earlier, because many of the ground motion models are generic soil models, we also give the amplification factors relative to Category III on Figs. 5.3.7a for sand-like sites and 5.3.7b for till-like sites. Also shown is the amplification factors relative to Category III for the rock set. Figure 5.3.7c shows the envelope, median and 1-Sigma amplification factors computed for the IIb sand-like category relative to Category III. Comparing Fig. 5.3.7c with Fig. 5.3.3b shows that the uncertainty is much larger if base case is taken as Category III as compared to rock (Category I). This increase in uncertainty is to some unknown extent an artifact of our approach, but most of it is, in our opinion, real.

5.4 Site Specific Correction Factors

The approach here is similar to that discussed above in Section 5.3 except that a specific analysis is performed for each site rather than for a set of sites falling into a particular category. However, it is still necessary to model the uncertainty in our knowledge of the random variation in the soil properties over the site (in the same layer), depth to bedrock and the randomness introduced by the dynamic response to all future earthquakes. We propose using an approach similar to the one discussed above in Section 5.3 except the variation in the soil parameters would be governed by conditions at the specific site.

One example of the differences in amplifiction factors that can result between using a category approach and a site specific approach is illustrated in Fig. 5.4.1. For the site specific case we selected sand-like Category IIb and greatly reduced the COV used to simulate the site models. We used a COV of 5% on depth and rock shear wave velocity and a COV of 15% for the shear wave velocity of the soil column. We selected these values to be consistent with the range of uncertainty that one would have relative to these parameters at any particulsr site. Also shown on Fig. 5.4.1a, for comparison, is the curve for sand-like category IIb from Fig. 5.3.3a. These amplification factors are relative to rock. As expected, the site specific case has higher amplification factors and less dispersion about the peak. Figure 5.4.1b shows similar comparison for the till-like IIb case. The difference between site specific and the Category approach is similar.

Figure 5.4.2 taken from Appendix B shows a specific analysis for the soil column at the Zion site which would fall into sand-like Category IIb. The amplification factors are much higher at Zion. There are several reasons for this:

1) The Zion site soil column model had lower damping.
2) There was a larger contrast in shear wave velocity between bedrock and the first layer of soil.
3) Soil layering in the Zion site's soil column model also introduced added amplification.

Figure 5.4.3 shows the envelope, median and 1-Sigma amplification factors for the site specific case shown on Fig. 5.4.1a. Comparing Fig. 5.4.3 to Fig. 5.3.3b shows that (as would be expected) the uncertainty is reduced for site specific case. However, considerable variation still exists from earthquake to earthquake.

5.5 Other Approaches

At the Ground Motion Panel Feedback meeting of June 27, 1984, and in subsequent interaction with the panel members after the meeting, questions were raised about the adequacy of our proposed approach. In particular it was suggested that surface waves and other non-vertically incident waves could be important. Also focusing and defocusing of rays are not considered.

To include such factors would require a very detailed site specific analysis. For a Western U.S. site where the configuration of major near-by active faults is known, it would be possible to perform such complex studies and examine such issues. Although, it should be noted that such studies are almost beyond the current state-of-the-art and few even limited studies have been performed to address such issues. For the EUS these questions are even more difficult to assess because it is assumed that the earthquakes occur randomly around the site. Thus, it is very difficult to perform such detailed site specific studies.

Our proposed approach evolved from the following observations. First, it is very difficult to separate out the wave type in the strong motion accelerograms. In part because strong motion accelerograms are generally recorded within 100km of the source. Our analysis shows that much of the hazard is contributed by earthquakes located within 100km of the site. It must also be kept in mind that we are primarily interested in the high frequency end of the ground motion spectrum--i.e. for frequencies greater than 1 or 2Hz.

Even for distant sources--in particular site amplification observed at sites from underground nuclear explosions (Hays, 1980; Murphy et al, 1971); it has been found that the simple linear theory similar to our proposed approach, has been adequate to explain the important feature of the observed ground motion.

Also to address this issue as part of NRC funded SSMRP, we funded an analysis using earthquake source modeling to (in part) characterize the type and direction of incoming seismic waves at a typical EUS site as compared to WUS site (Apsel, et al, 1980). This analysis found for a soil site (falling into our IIb category with a soil depth of about 100' over a bedrock with a shear wave velocity of 3.3km/Sec) that all of the energy emerged almost vertical at all frequencies. For a deeper soil WVS site the results were much different with waves generally emerging at angles of 20° or more relative to the vertical. It is assumed that the results for a deep soil EUS site would be similar.

The issue of ray focusing is very difficult to deal with given the relatively random nature of seismic activity around any particular site. Except for a few very special potential earthquake locations around a few sites, it is not evident how to even approach this question.

Finally in choosing your weights it should be kept in mind that one of the purposes of this study is to identify sites that require a detailed site specific study. Such studies are costly. Thus, the decision to require such studies should be based on an approach which adequately, but not too conservately, bounds the uncertainties in the estimate of the seismic hazard at any particular site--including the effect of the local soil configuration. One of the objectives of this study is to provide NRC with the best possible estimate of the seismic hazard at each site so NRC can make an informal judgment.

It is our judgment that to do this requires at least the sites be put into categories such as we have proposed and correction factors be included in the analysis. However, your judgment may well be different--which is, of course, why we are soliciting your responses about how to best incorporate the uncertainty about the influence of the local site conditions on the estimated seismic hazard at any specific site.

5.6 The Contribution to the Uncertainty in the Ground Motion Model due to Different Sites.

We noted earlier that the uncertainty in the median estimate of ground motion for only given model is made up of several contributors. Specifically, the ground motion models that were used in our analysis are of the form

$$\ln a = C_1 + C_2(I_0 \text{ or } M) + C_3 R + C_4 \ln R + (\text{error term}) \qquad (5.6.1)$$

The error term is made up of the contribution to the uncertainty from source, travel path, site and building effects. Building effects entered because in developing Eq. (5.6.1) intensity values were used. For typical sets of Western U.S. data

$$\sigma_{\ln a} \sim 0.6$$

To get a handle on the appropriate value of $\sigma_{\ln a}$ to use in the analysis if the site remains fixed we analyzed the data from several sites which had experienced a number of earthquakes. In addition, some data is available from underground nuclear explosions.

Figure 5.6.1 from Lynch shows the reduction in the dispersion of the same data when they are analyzed by a <u>covariance</u> analysis that explicitly includes each site rather than a typical regression analysis. Briefly, covariance analysis relates a component of spectrum SV at period i recorded at K stations (S_{ik}) to the yield of events detonated in a restricted area. The statistical model has the form

$$SV_{ik} = A_{ik} W^{B_i} \qquad \begin{array}{l} i = 1, 2, \ldots, I \\ k = 1, 2, \ldots, K \end{array}$$

Covariance analysis determines for each component at each period, i, a yield scaling exponent B_i, a standard error of estimate σ_i, and K sets of amplitude coefficients A_{ik}. The amplitude coefficients A_{ik} implicitly reflect the average distance from the event area to the recording station, local station amplification and any factors associated with the transmission path. The standard errors of estimate σ_i reflect variance due to neglected source parameters, transmission path factors for each station and differential changes in the average distance to each recording station.

Source and travel path variations for each site were minimized by restricting the data to only UNEs located on Pahute Mesa. The level of ground motion was low so that site soil nonlinear effects should be small. Figure 5.5.1 shows that fixing the site and reducing the possible source and travel path variations significantly reduce the scatter of data about the mean. A significant variation can still be attributed to relatively minor changes in travel path and source conditions.

If a given site has experienced a number of earthquakes and has records of the ground motion, then it is possible to determine if the site generally amplifies ground motion relative to typical correlations such as those developed by McGuire. It is also possible to determine if the data at a given site are less dispersed than the more general data set for a number of sites. The difficulty is to assess the role that site response factors play relative to source and travel path factors. Source and travel path variations are extremely important. It is difficult to account directly for these factors other than by the simple approach of grouping the available data so that these factors are minimized.

The El Centro and Ferndale sites have the most complete data set: Table 5.6.1 gives the earthquake data recorded at the El Centro site, and Table 5.6.2 gives the data for Ferndale. A number of different references were used to develop these tables, and different data sets often have significant differences among themselves; no significant effort was undertaken to reconcile the discrepancies among different data bases.

Both of these sites are deep soil sites, although the overall soil depth is greater at El Centro than at Ferndale, where the earth is somewhat stiffer than at the El Centro site.

Sufficient data have been recorded at these two sites to compare the peak acceleration to the mean predicted by typical correlations among peak accelerations, site type, earthquake magnitude, and distance. For comparison, the most recent correlation developed by McGuire (1978) was chosen as representative. For soil sites, McGuire determined that

$$a = \frac{24.5 \exp [0.89M]}{R^{1.17}} \quad ; \quad \sigma_{\ln a} = .62 \quad , \qquad (5.6.2)$$

where

M = Local Richter magnitude

R = Distance from energy release

σ = Standard deviation

Figure 5.6.2 shows a comparison of the recorded acceleration at the El Centro and Ferndale sites normalized by exp 0.89M as a function of R. Also shown is the median normalized line given by Equation 5.6.2 and the ± one-sigma lines. It is evident from this figure that consistently higher-than-average peak accelerations are recorded at the Ferndale site during the earthquakes. The El Centro site appears to have average acceleration.

In order to quantify the dispersion of the data, separate regression analyses were performed for the data at the El Centro and Ferndale sites. The results of these analyses are:

$$\ln(a) = 4.82 + 0.52M - 0.83 \ln(r)$$

$$\sigma_{\ln a} = 0.39$$

for Ferndale, and

$$\ln(a) = 4.12 + 0.53M = 0.85 \ln(r)$$

$$\sigma_{\ln a} = 0.67$$

for El Centro.

There is significantly less scatter to the data at the Ferndale site than to the data at the El Centro site. The data at El Centro have about the same

standard deviation as the more general data set used by McGuire, which included eight El Centro records and nine Ferndale records. Although the distances R for the Ferndale events are less certain than for El Centro events, no systematic error exists, S. Smith (1978), and it is unlikely that the errors are large enough to significantly change the conclusion reached above.

We also examined the Oroville data set. We performed regression analysis on the data in Seekins and Hanks (1978) to determine how the error term was reduced going from the general data set to a fixed site. We only examined (for the fixed site cases) those sites at which eight or more earthquakes were recorded. We obtained

Sigma (lna) =	0.56	General data set
	0.42	Johnson Ranch Station
	0.26	Station 5
	0.61	Station 1
	0.36	EBH Station

The results are in reasonable agreement with the results for Ferndale, El Centro and underground nuclear explosions data. There is considerable scatter to the data making the choice of appropriate value to use difficult. The only trend that may exist is that the "stiffer sites" (Ferndale, Johnson Ranch, Station 5, EBH) show lower value than deep, softer stations (El Centro and Station 1). McCann and Boore (1983) and McCann (1983) attempted to sort out the various contributions to the uncertainty in the prediction of ground motions using data from the San Fernando Earthquake. McCann (1983) concluded that local site effects contributes about 30% of the uncertainty.

5.7 Summary of Proposed Approach

In Section 6.4 we ask you to consider the discussion in Sections 5.1 - 5.6 and to select specific models. In this section we want to ensure that the questions are sufficiently specific. This section should be read in conjunction with Section 6.4

In Question 6.5 (Table 6.7) no specific approach/set of correction factors is implied. What we are asking is, in your judgment, how much different would the various GMP's be if the site in question was located on hard rock or shallow soil (50'-200' deep), as compared to the values of the GMP's predicted by the base case models.

In Question 6.6 (Table 6.8) we are addressing the adequacy of various ways to correct for the effect of the local soil column on the GMP's. Methods 2 and 3 are intended to be correction factors based on the approach discussed in Section 5.3; however, both method and--site specific correction--are meant to be as general and a complete analysis as required to correct for the factors you give in Table 6.10

In Question 6.7 we want you to specify the simple correction model you wish us to use.

We indicated that if you do not supply a specific model we would use the correction factors determined by Joyner-Boore, 1982--Curve 1 on Figs. 5.7.1. We selected this model as the "fall-back" case because in our opinion it is based on the best available data set. The difficulties with the other models are discussed in Section 5.3. You can select other models by providing a plot similar to Fig. 5.7.1 or the data to make such a plot. Note that we also need the correction factor for PGA and PGV illustrated in Fig. 5.7.1.

For categorical correction factors we will use the median curves to obtain the equivalent linear model shown in Fig. 5.7.2a for sand-like sites and 5.7.2b till-like sites. The uncertainty is modeled by assuming that the distribution is lognormal with a value for the standard deviation of the $\log_e$ of the correction factor equal to .5. We chose the equivalent linear model for the "median" curve because, as can be seen from Fig. 5.3.6, it falls between the "upper " and "lower" limit results. The system is chosen to model the uncertainty in damping and soil properties for the category.

Plot Symbol

1	J.B. (1982)
2	Trif & And (1977)
3	Trif & And (1977)
4	SEP

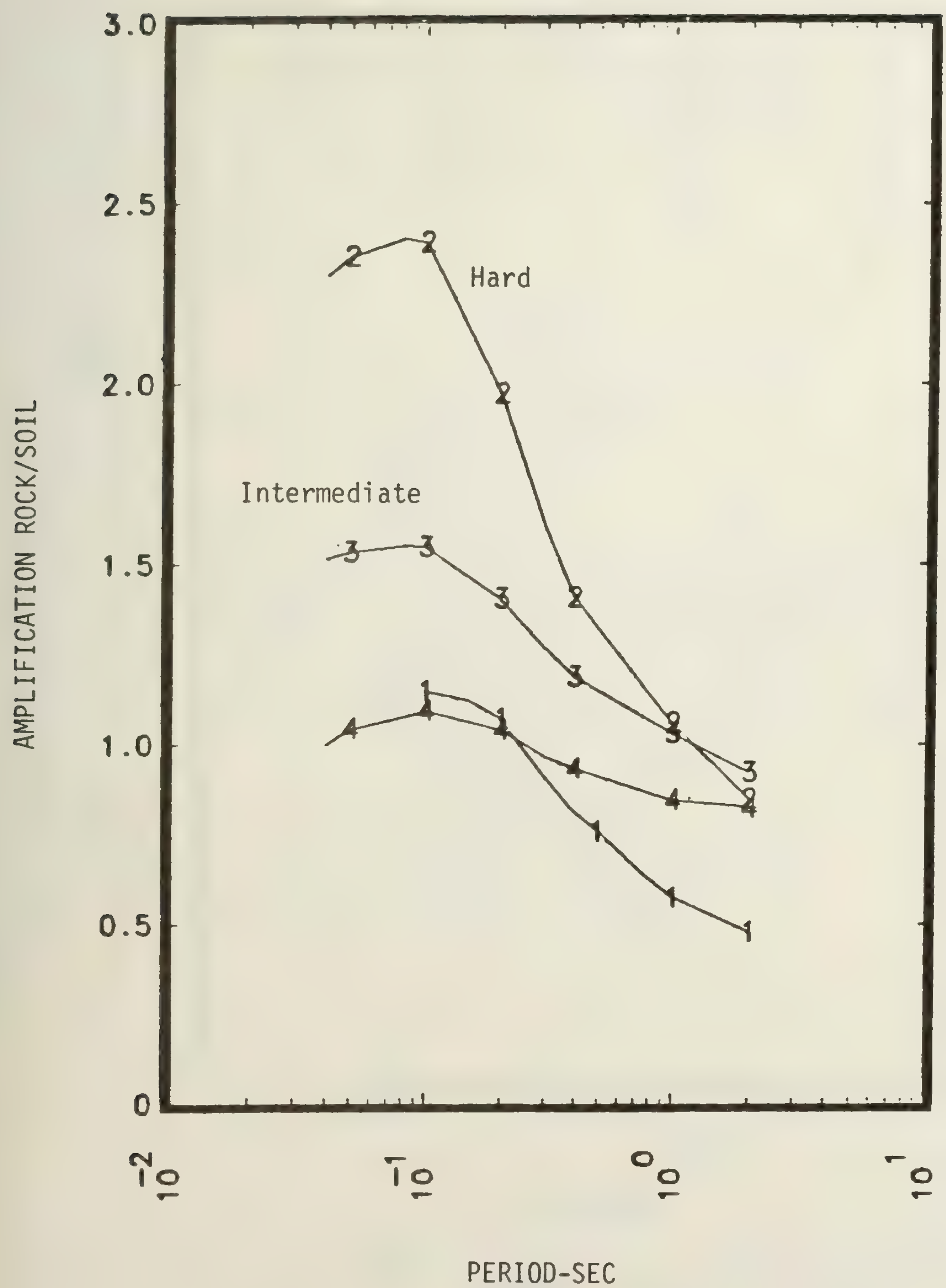


Fig. 5.3.1a. Simple correction factors obtained by regression analysis of WUS data.

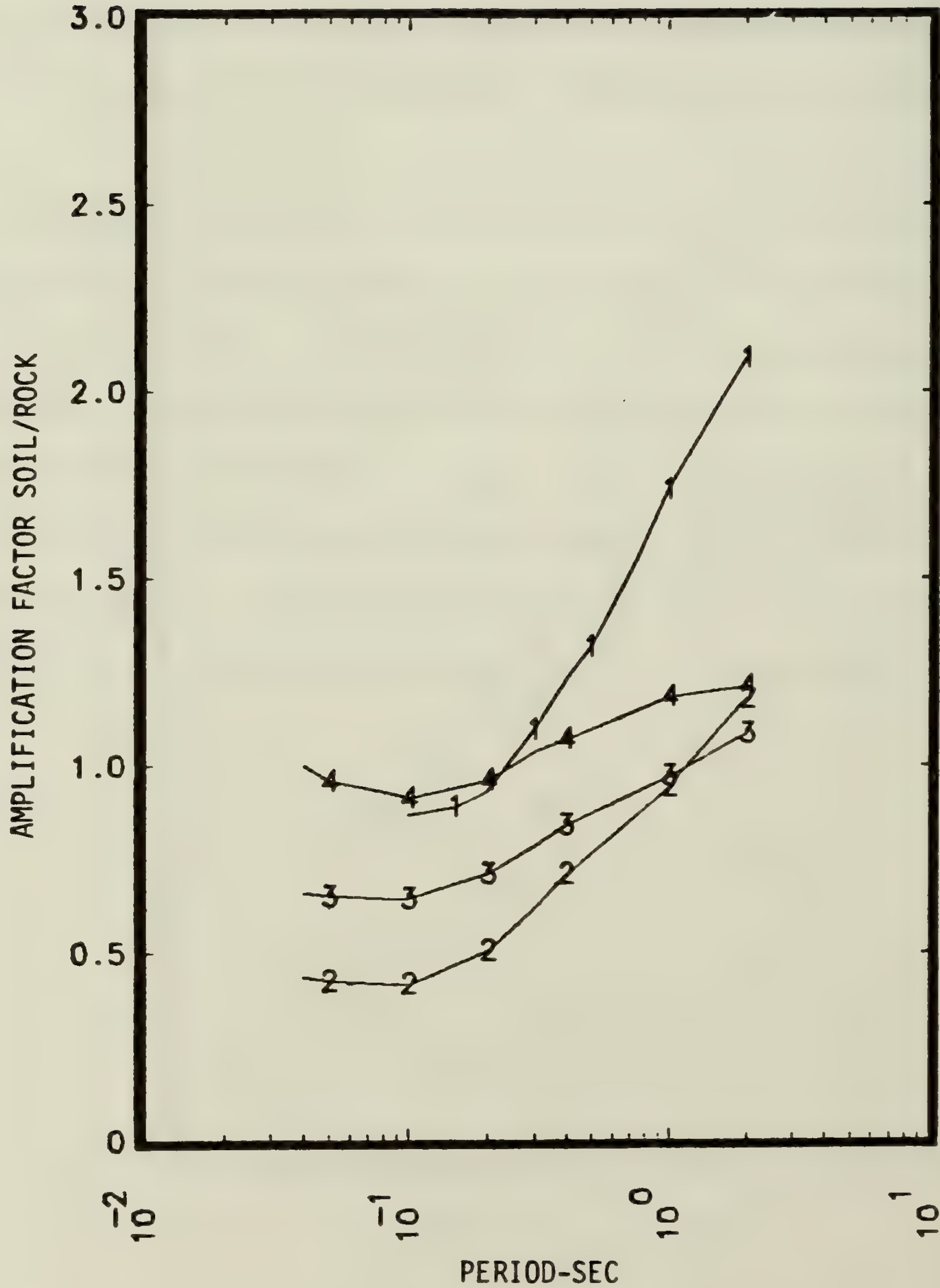


Fig. 5.3.1b. Same as 5.3.1a, except soil/rock.

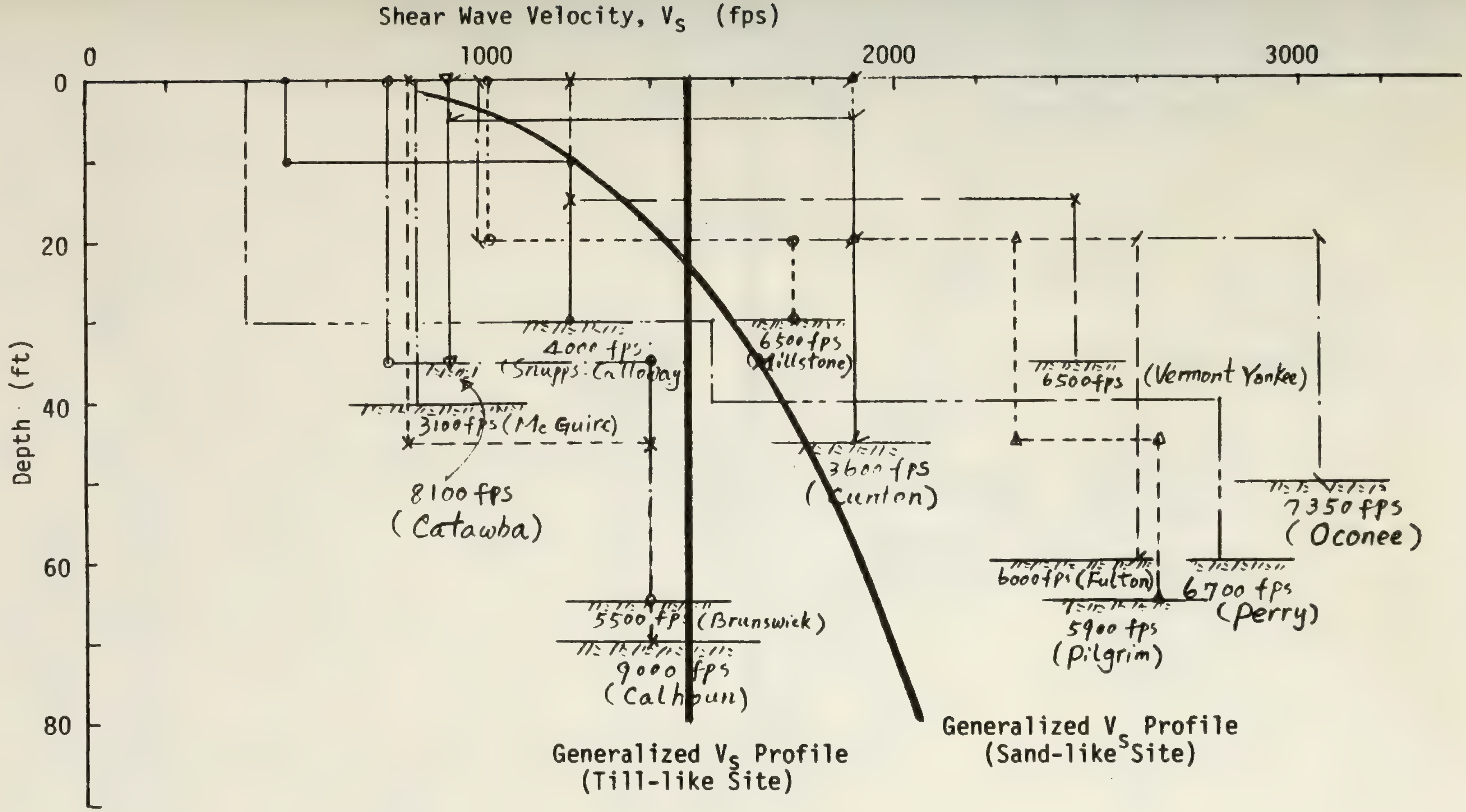


Fig. 5.3.2a Site Class IIa; 25 to 80 feet of Soil Over Bedrock

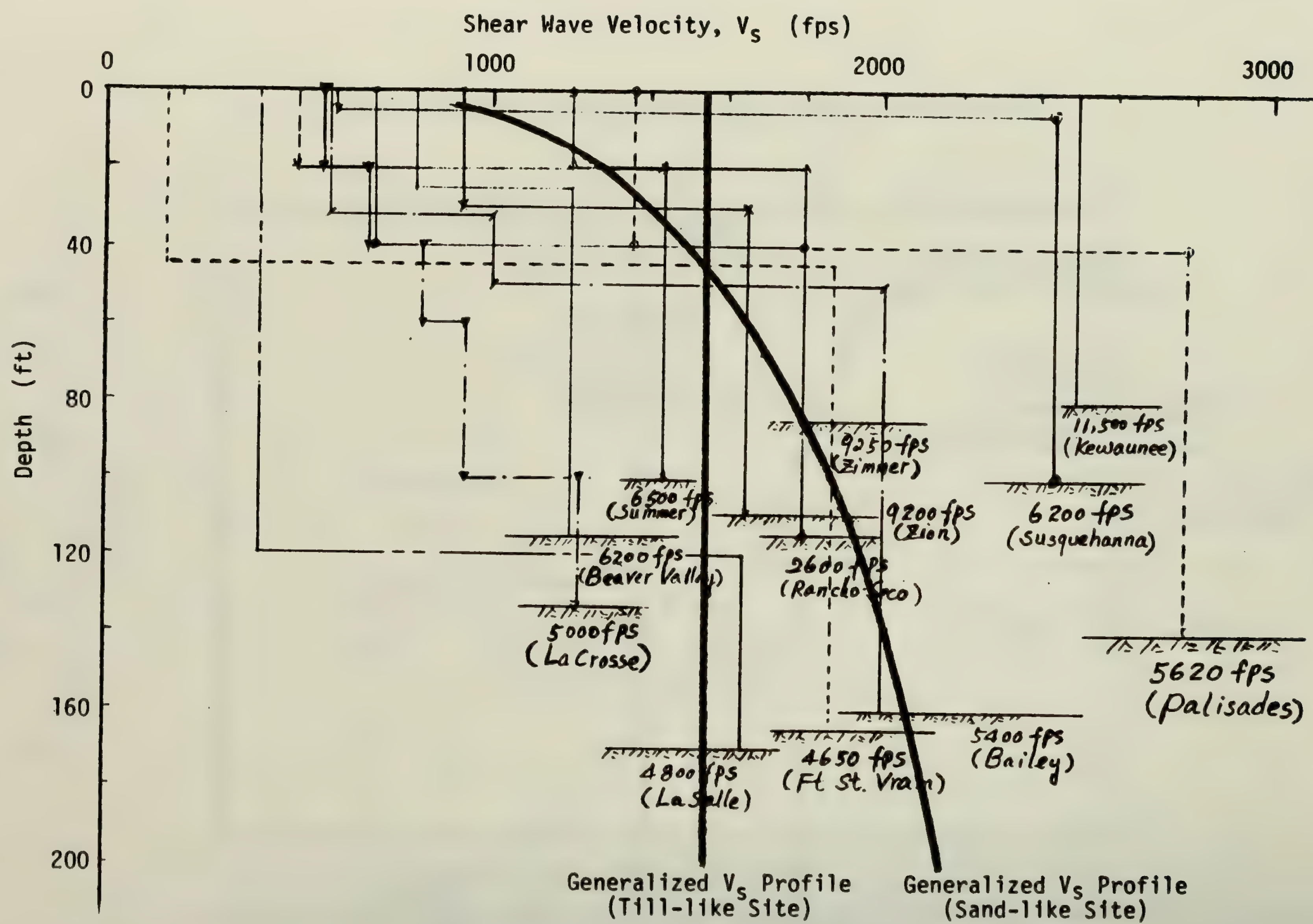


Fig. 5.3.2b Site Class IIb; 80 to 180 feet of Soil Over Bedrock

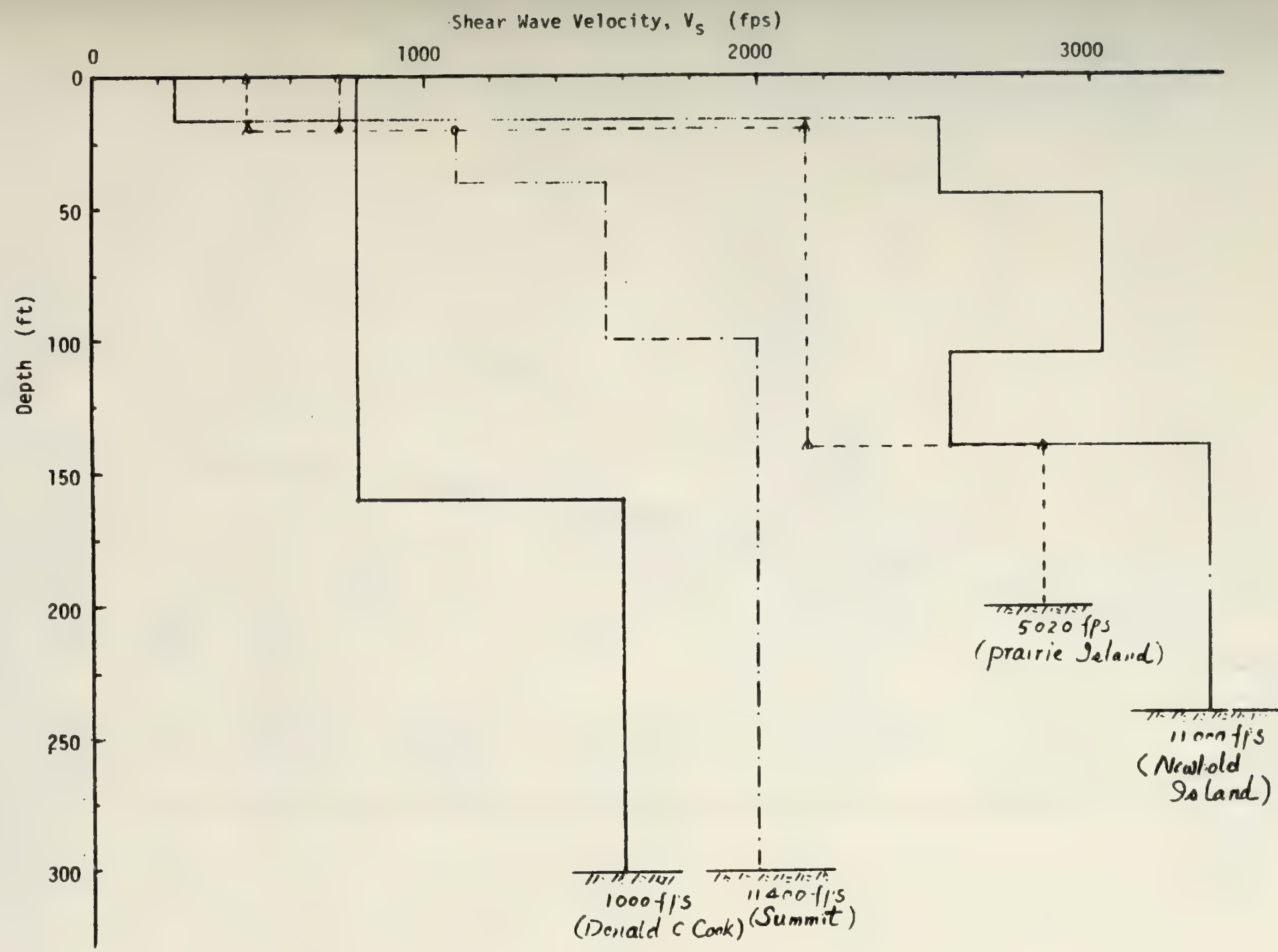


Fig. 5.3.2c Site Class IIc; 180 to 300 feet of Soil Over Bedrock

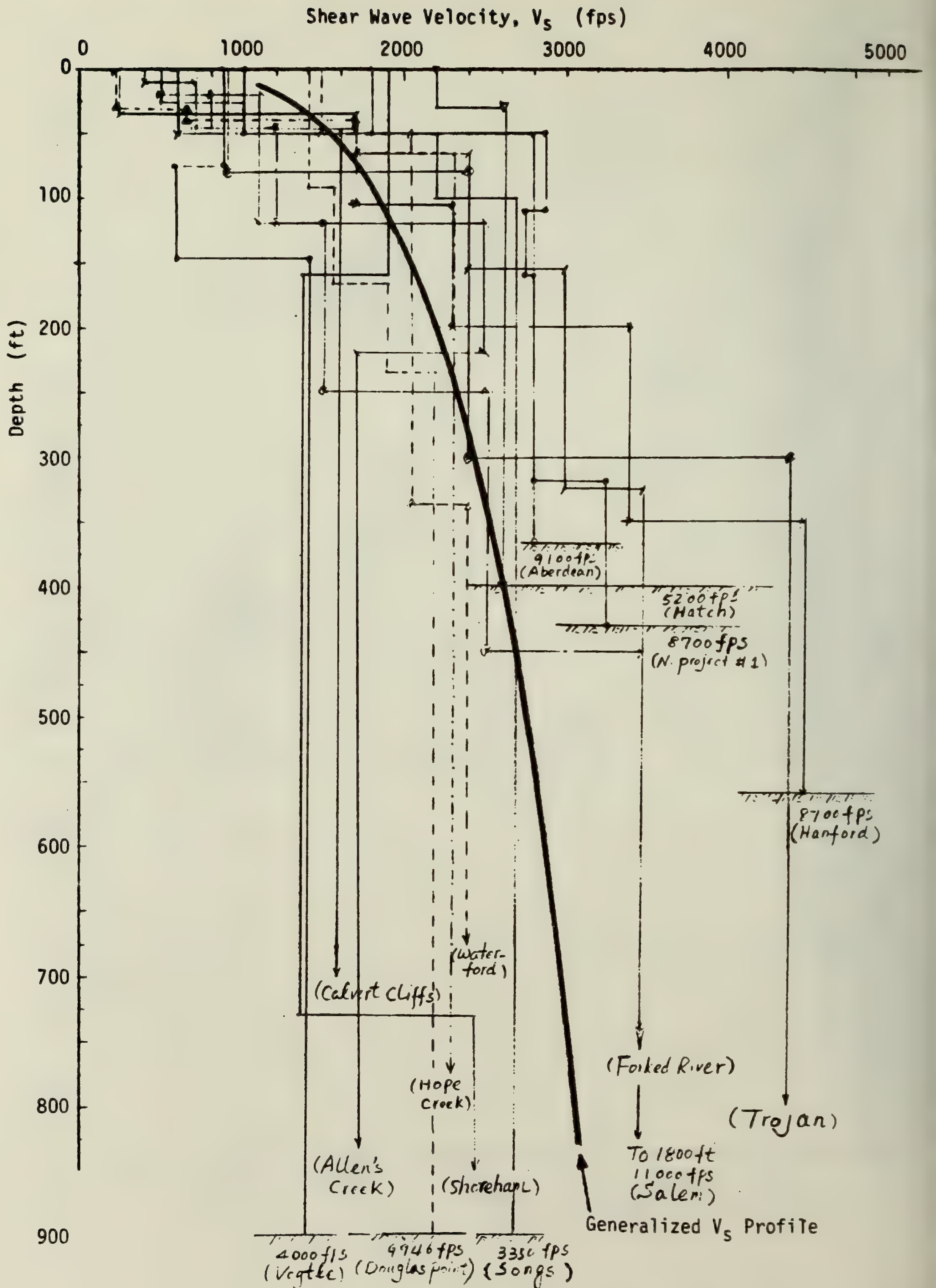


Fig. 5.3.2d Site Class III; Thick Soil - More Than 300 ft of Soil Over Bedrock

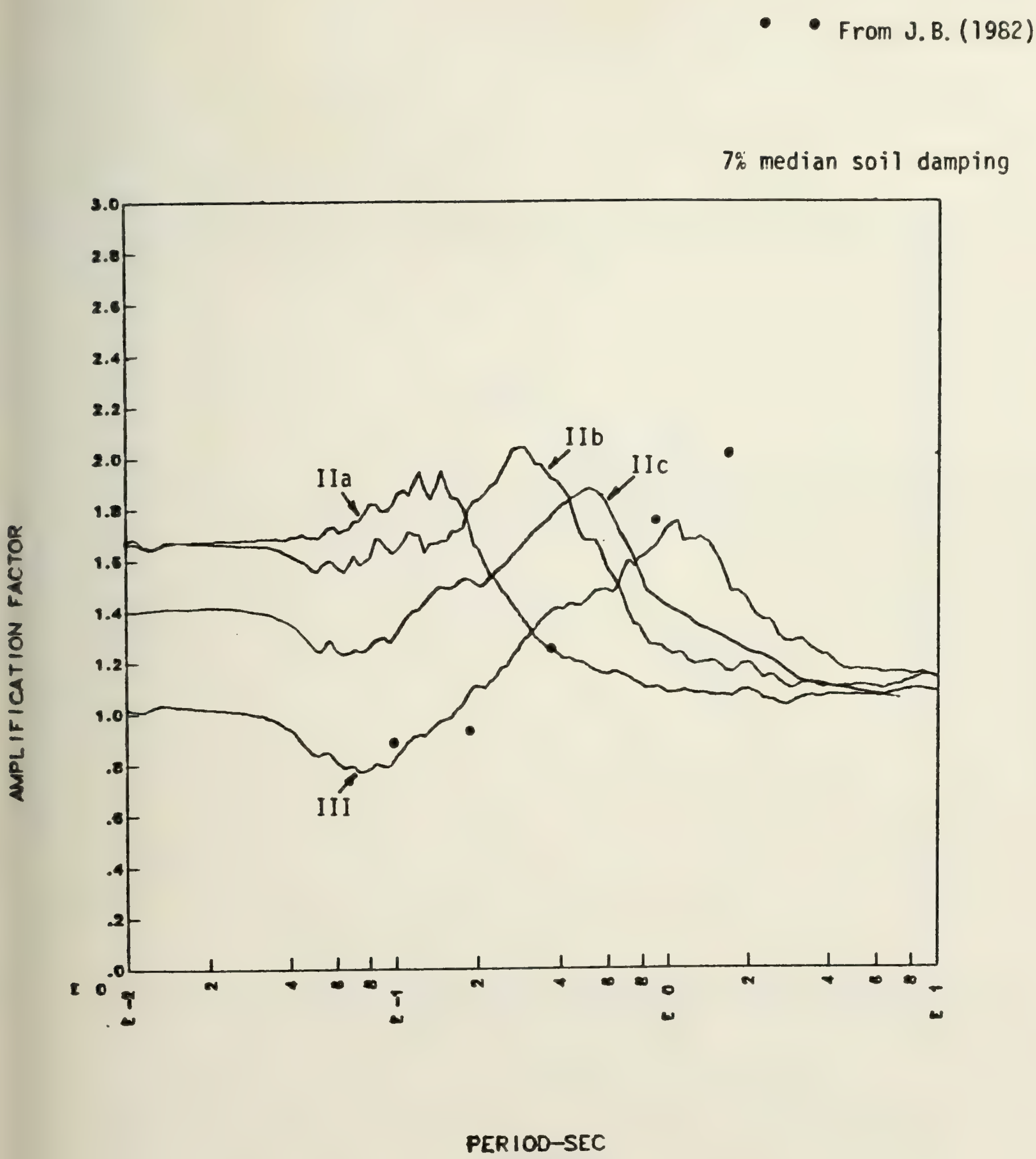


Fig. 5.3.3a. Comparison of amplification factors for sand-like sites for Categories IIa, IIb and III. Amplification is relative to rock. Also shown is the results from J.B. (1982) (Fig. 5.3.1), Regression Analysis.

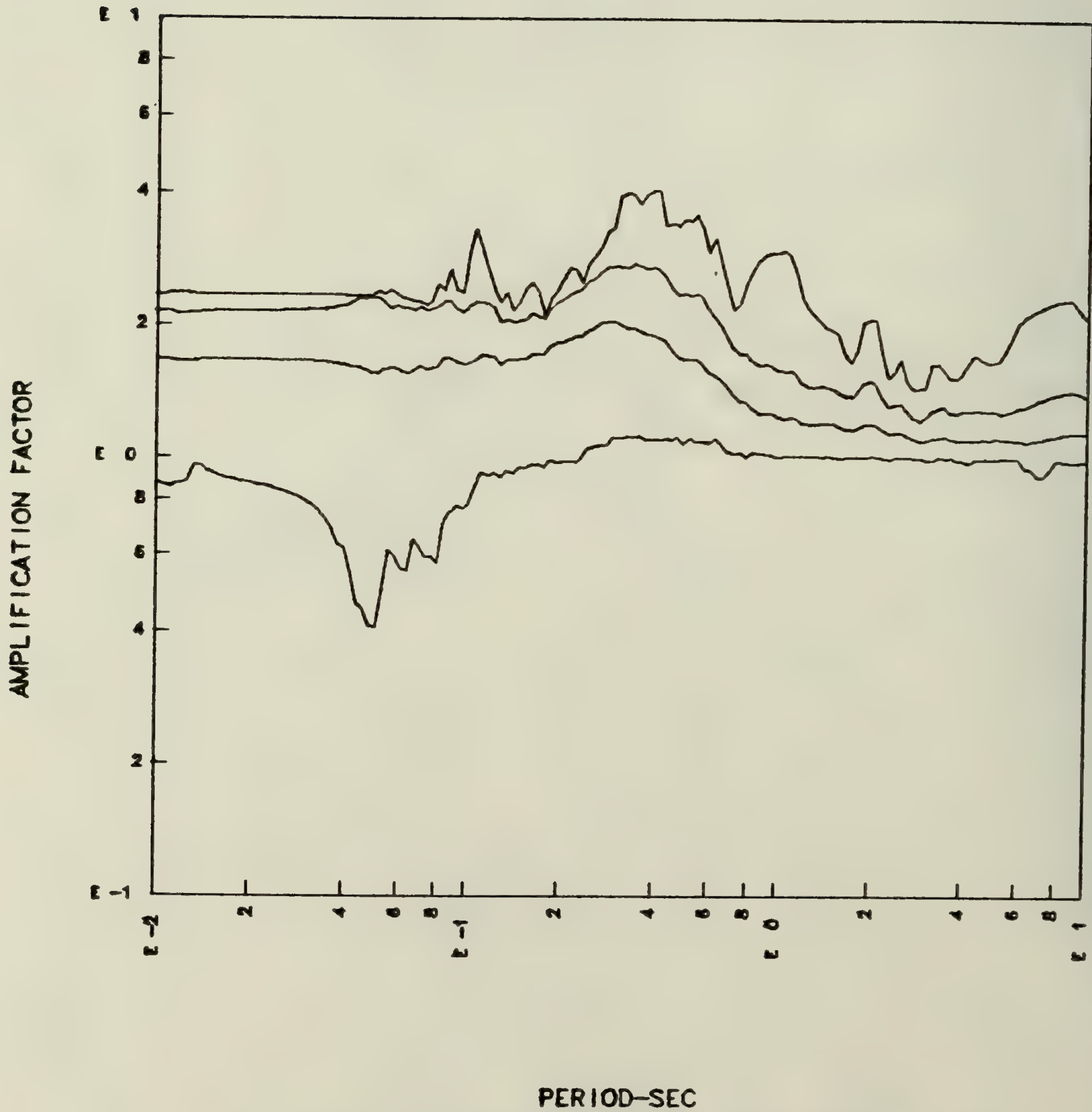


Fig. 5.3.3b. Envelope, median and 1σ amplification factors for sand-like IIb category relative to rock.

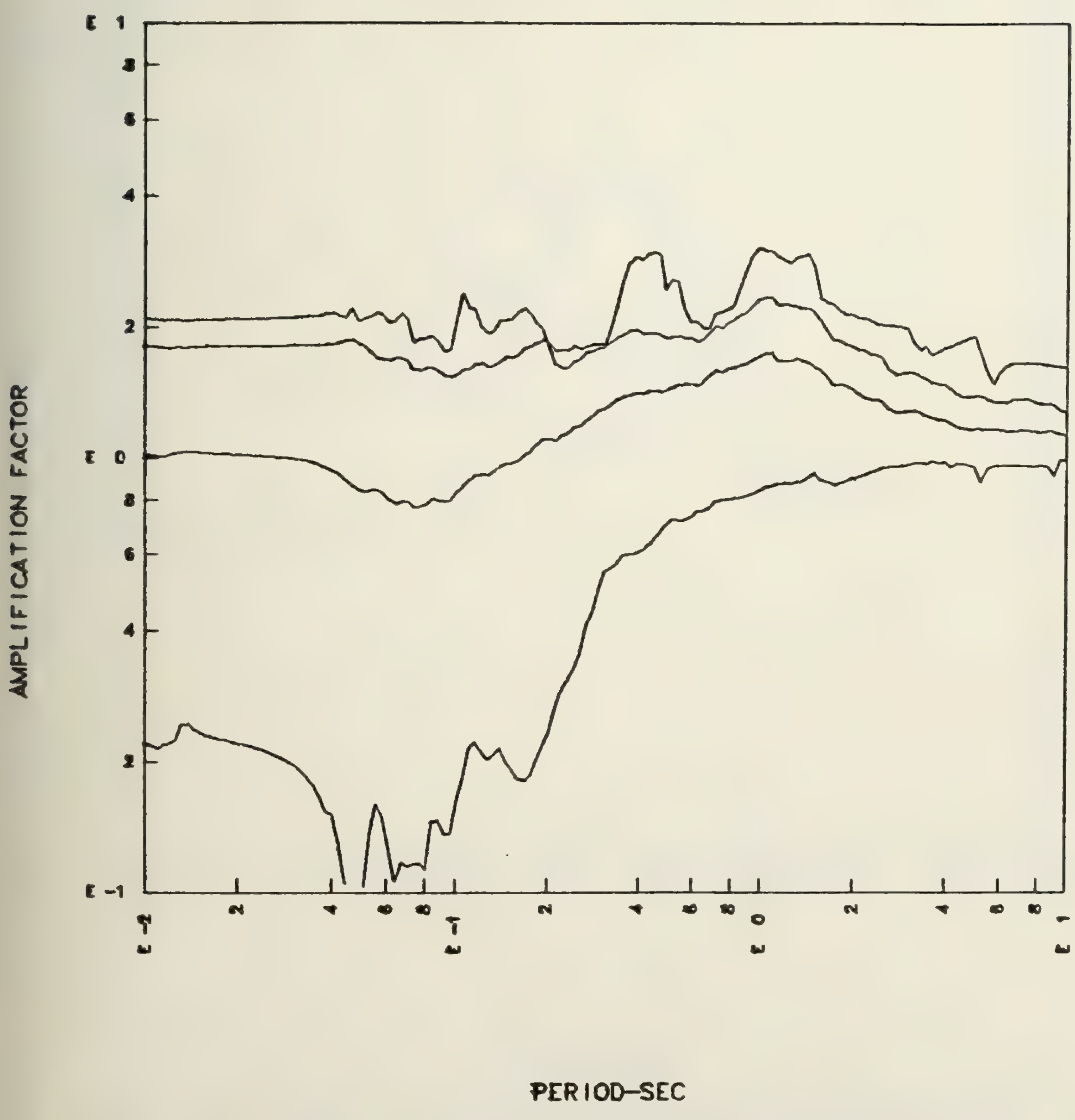


Fig. 5.3.3c. Envelope, median and +1σ amplification factors for Category III relative to rock.

7% median soil damp

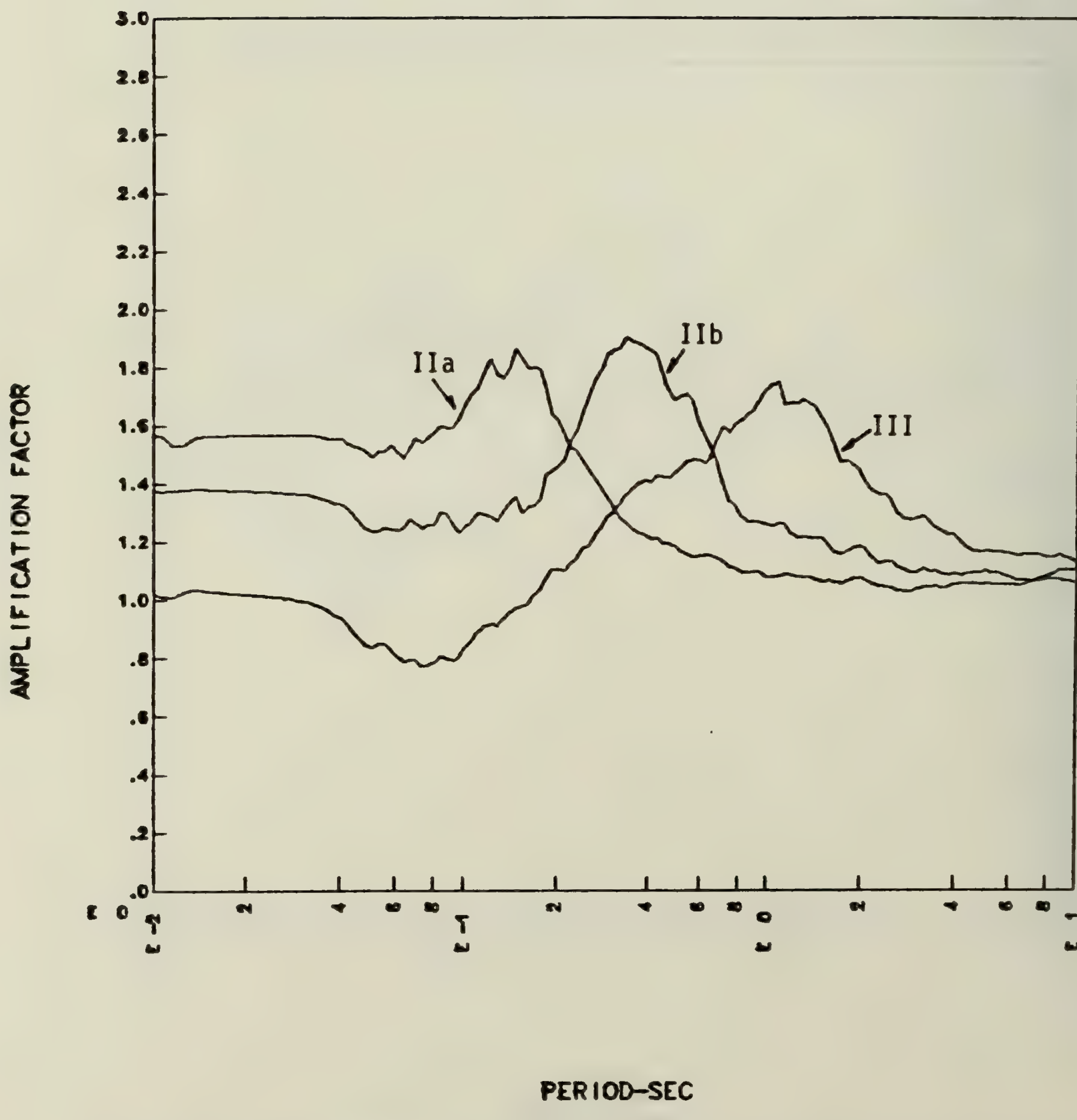


Fig. 5.3.4. Comparison of amplification factors for till-like sites IIa & IIb relative rock. Category III results also shown for reference.

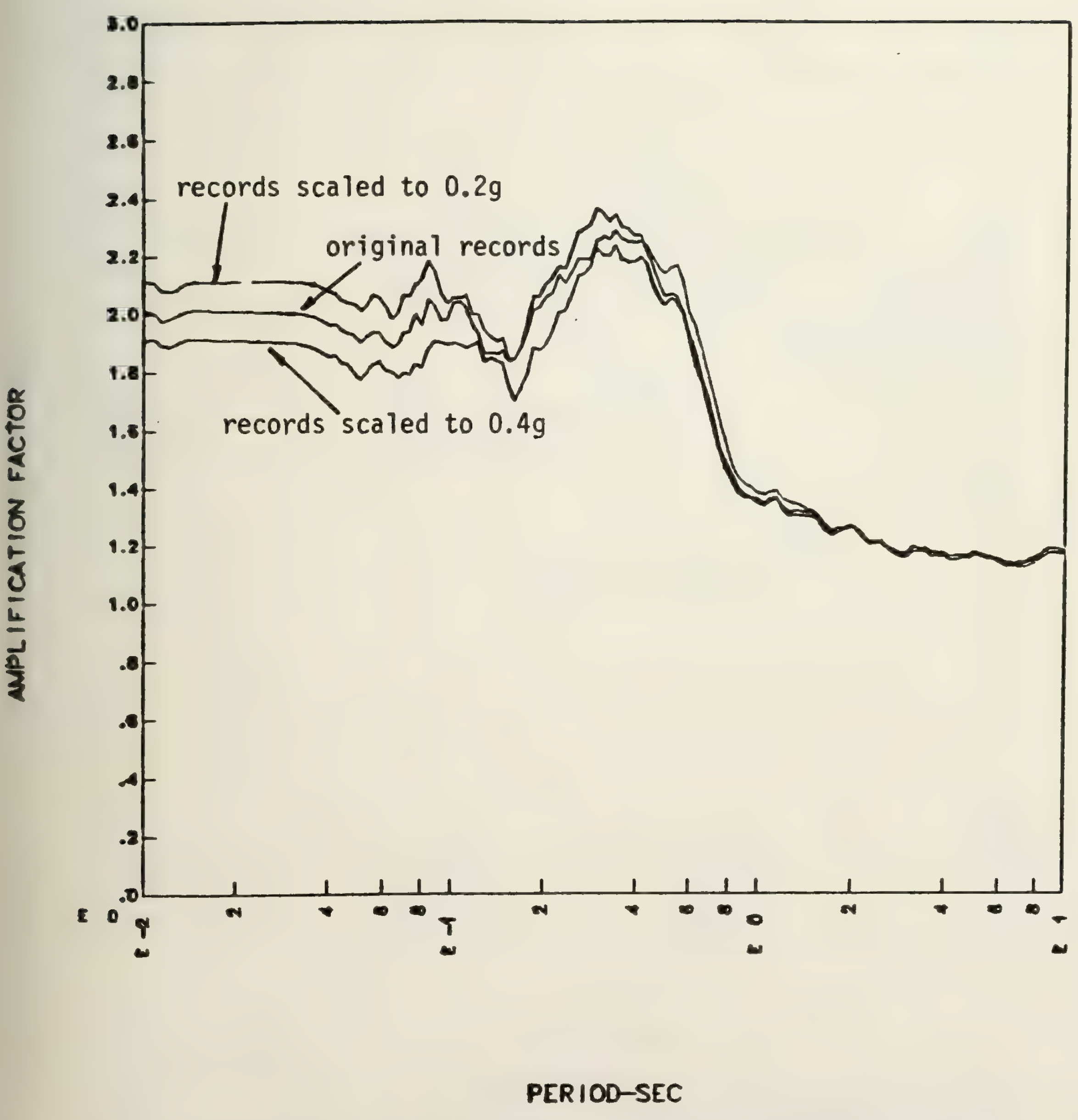


Fig. 5.3.5a. Effect of PGA on computed amplification factors--
equivalent linear analysis for sand-like
IIb category.

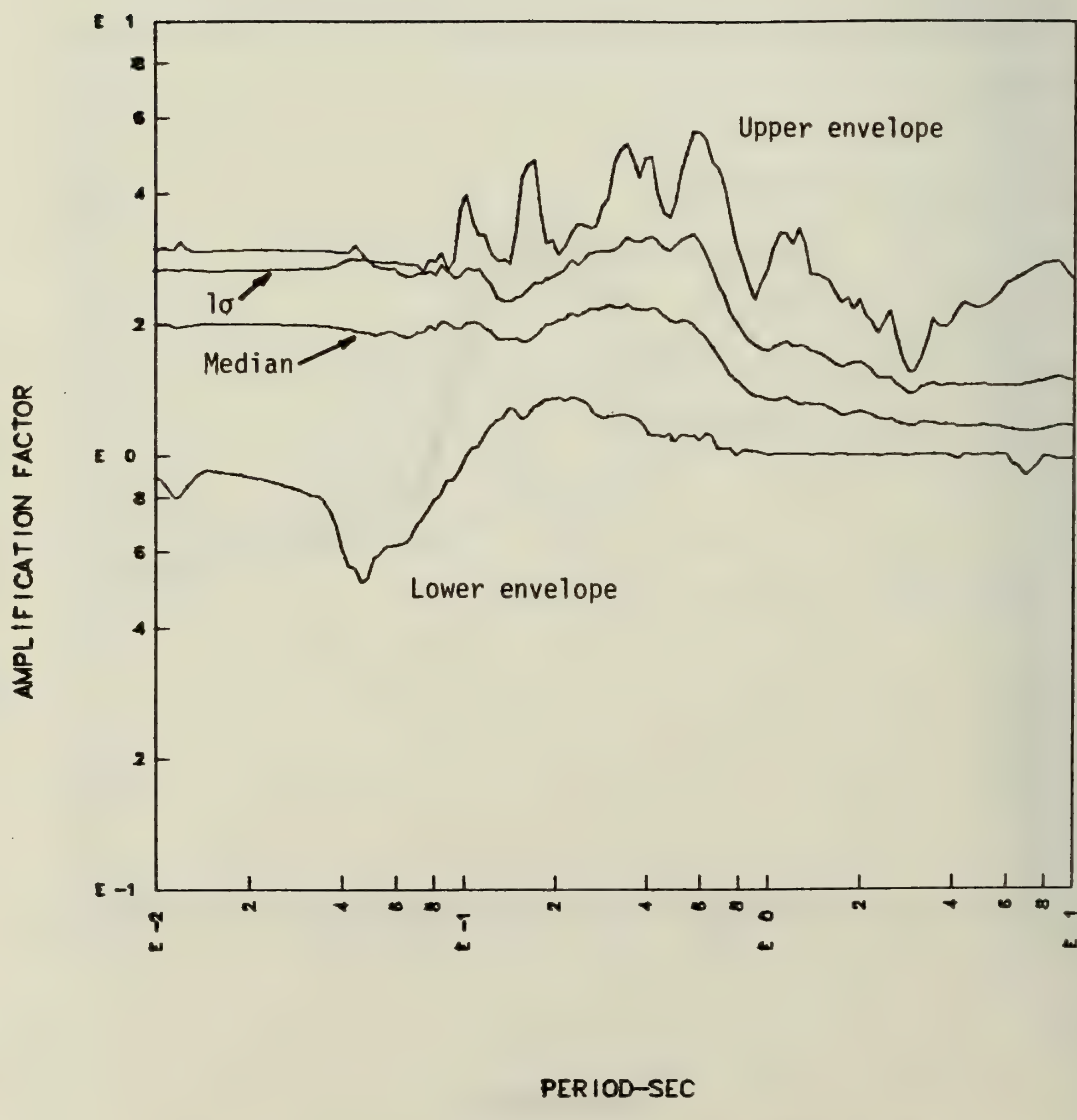


Fig. 5.3.5b. Effect of PGA on uncertainty of computed amplification factors--original records Category II2b sand-like relative to rock.

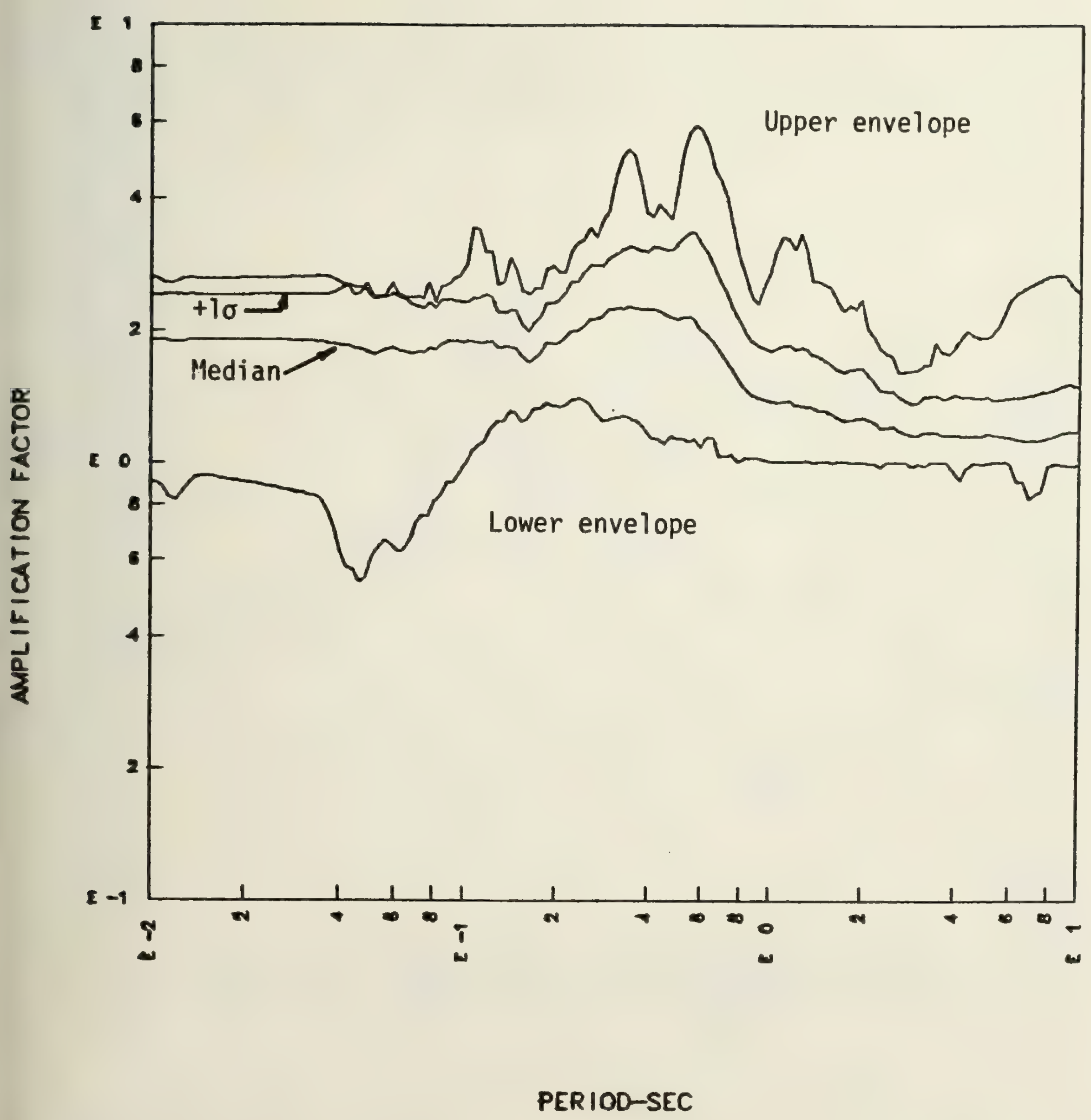


Fig. 5.3.5c. Effect of PGA on uncertainty of computed amplification factors for Category IIb sand-like relative to rock. All reacords scaled to 0.4g.

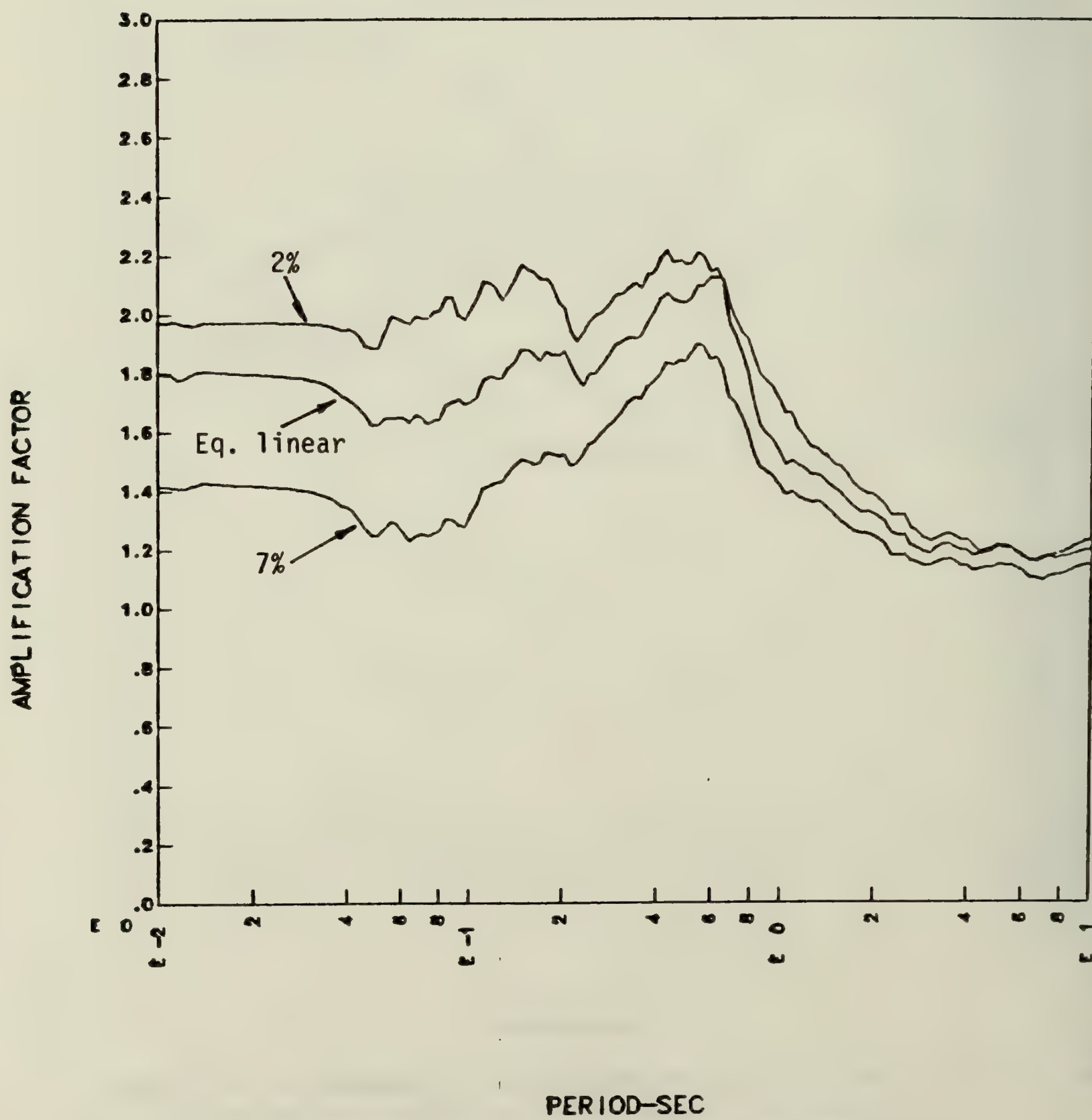


Fig. 5.3.6. Importance of damping illustrated for sand-like
IIc category.

7% Median Soil Damping

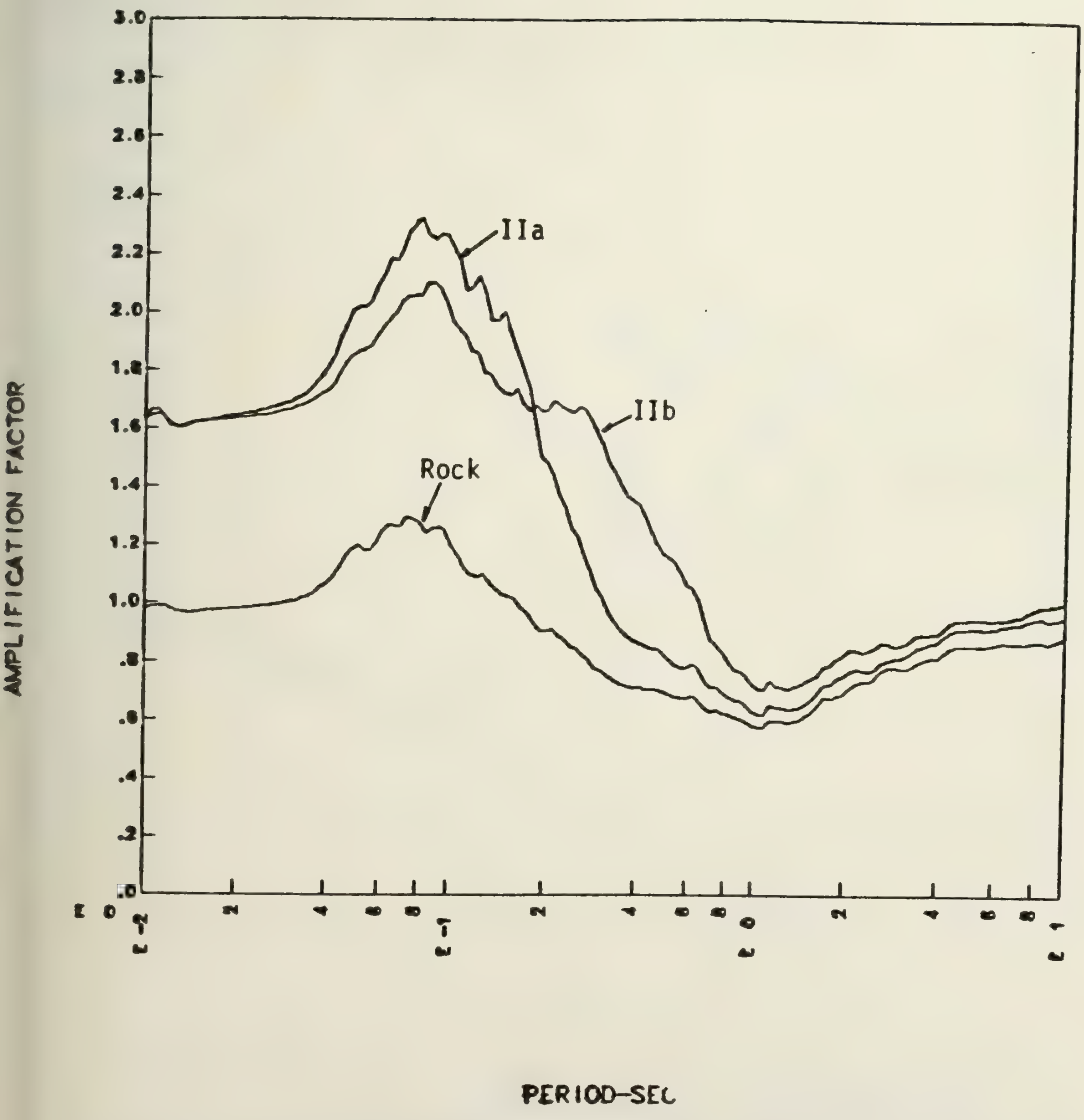


Fig. 5.3.7a. Amplification factors for sand-like soils relative to Category III. Also shown is the amplification of the rock category relative to Category III.

7% Median soil damping

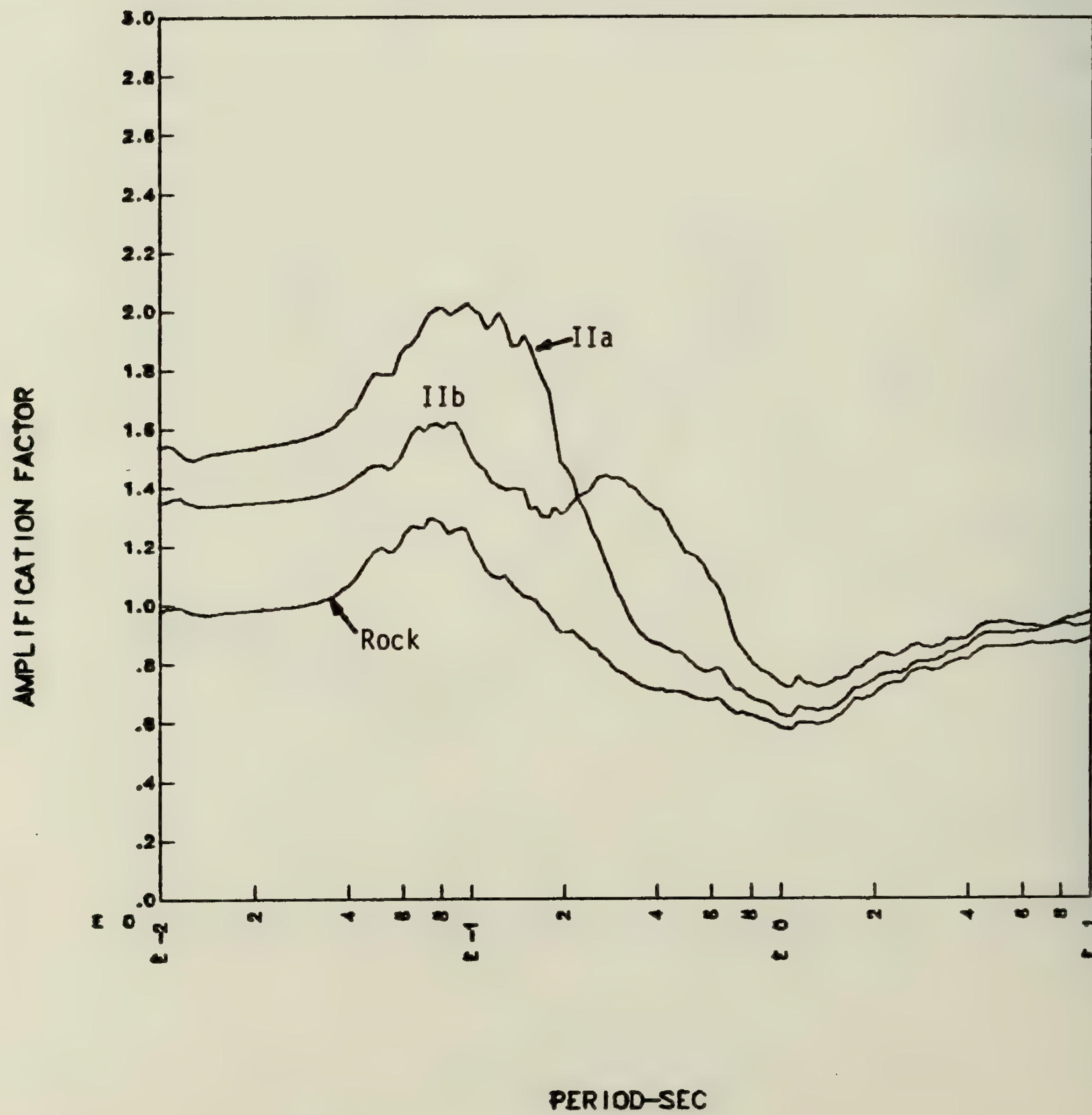


Fig. 5.3.7b. Amplification factors for till-like soils relative to Category III. The rock category relative to Category III is also shown for reference.

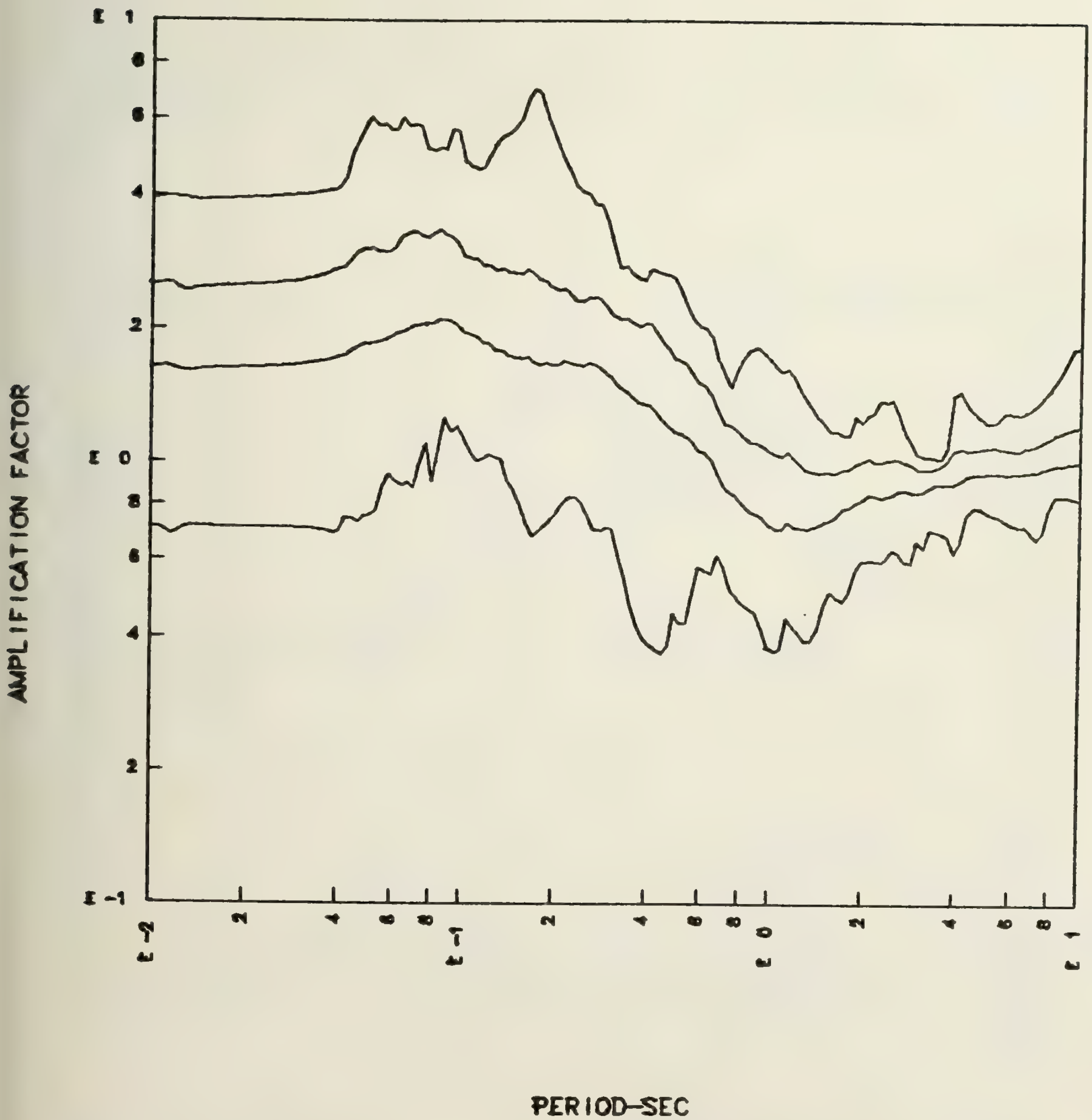


Fig. 5.3.7c. Increases in uncertainty in the computed amplification factors when Category III is used as reference. Envelope, median and +1σ curves shown for Category IIb sand-like relative to Category III.

"Site Specific" site COV on depth and rock shear wave velocity was reduced to 5%. COV of soil shear wave velocity was reduced to 15% relative to larger values used in the values used for simulation.

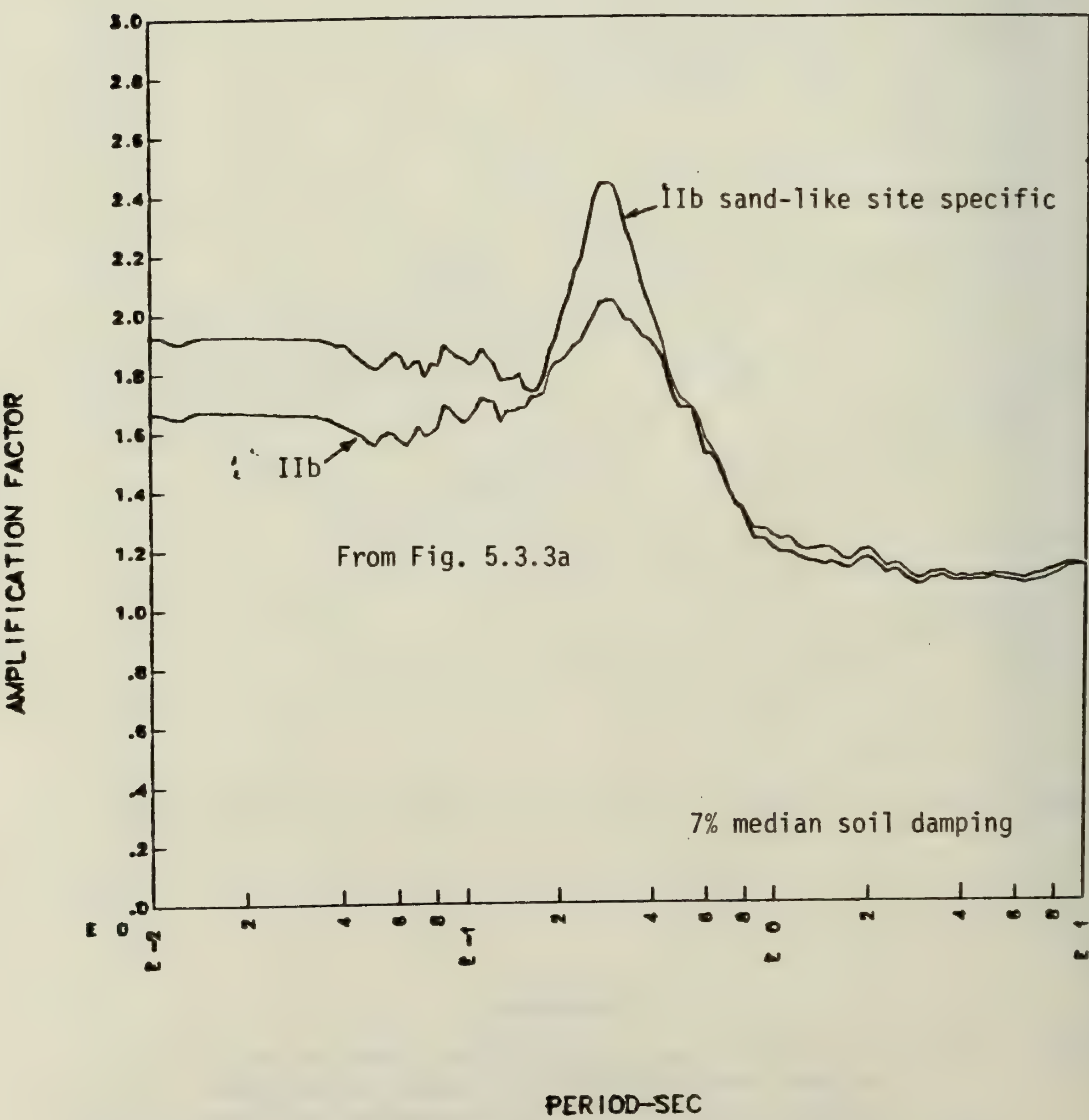


Fig. 5.4.1a. Comparison of computed amplification factors for a "Site Specific" case Category IIb sand-like to the median curve for Category IIb shown on Fig. 5.3.3a.

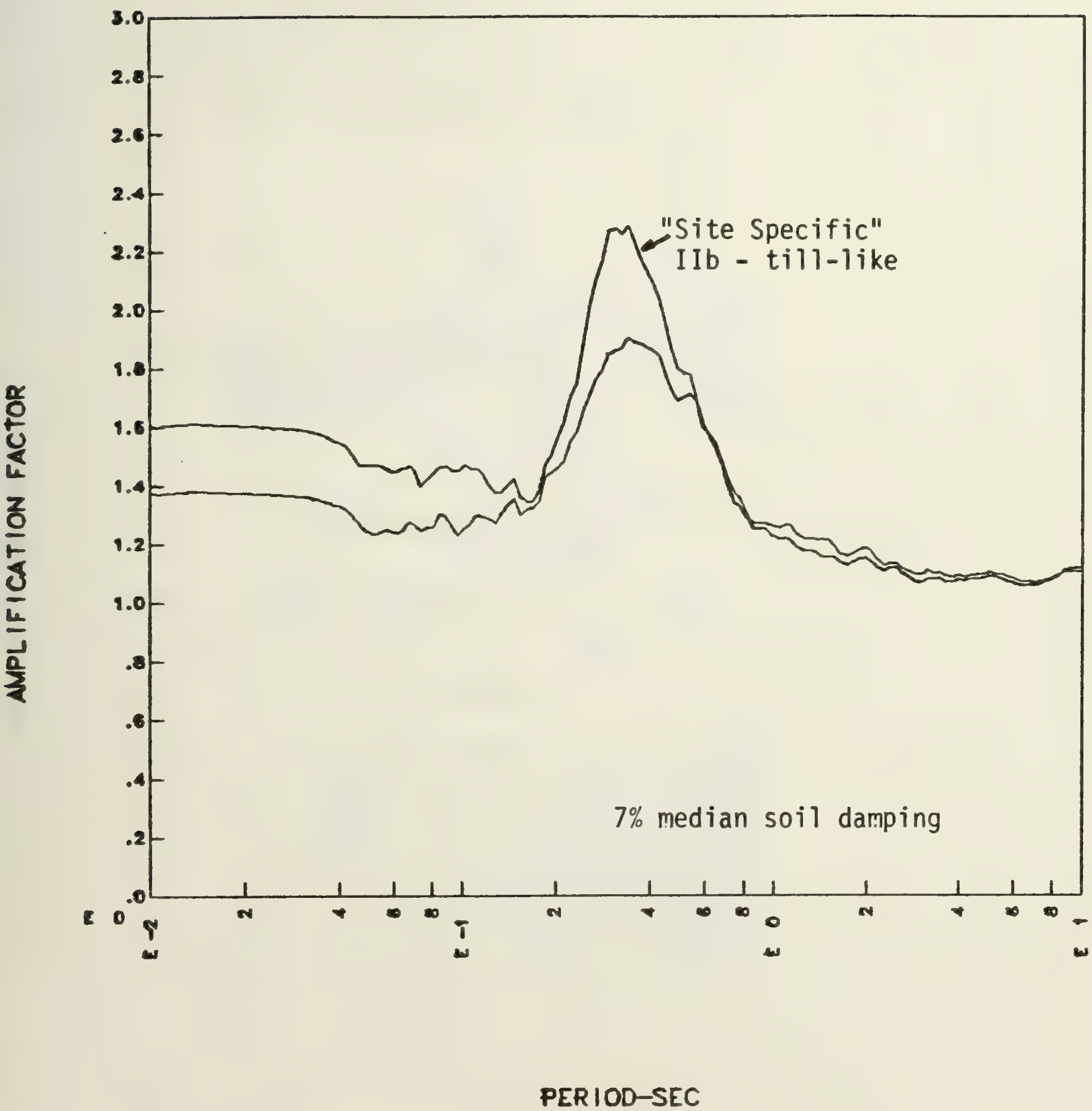


Fig. 5.4.Ib. Comparison of "Site Specific" case for till-like IIb site to general curve for till-like IIb sites shown on Fig. 5.3.4.

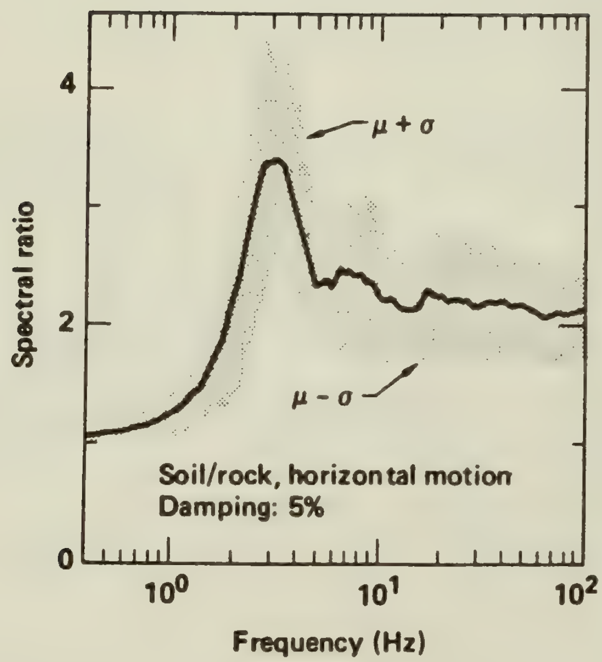


Fig. 5.4.2 Computed soil/rock spectral ratios for horizontal motion at the Zion site. The solid line is the mean of 30 spectral ratios, and the shading marks the variation in the mean (±1 standard deviation).

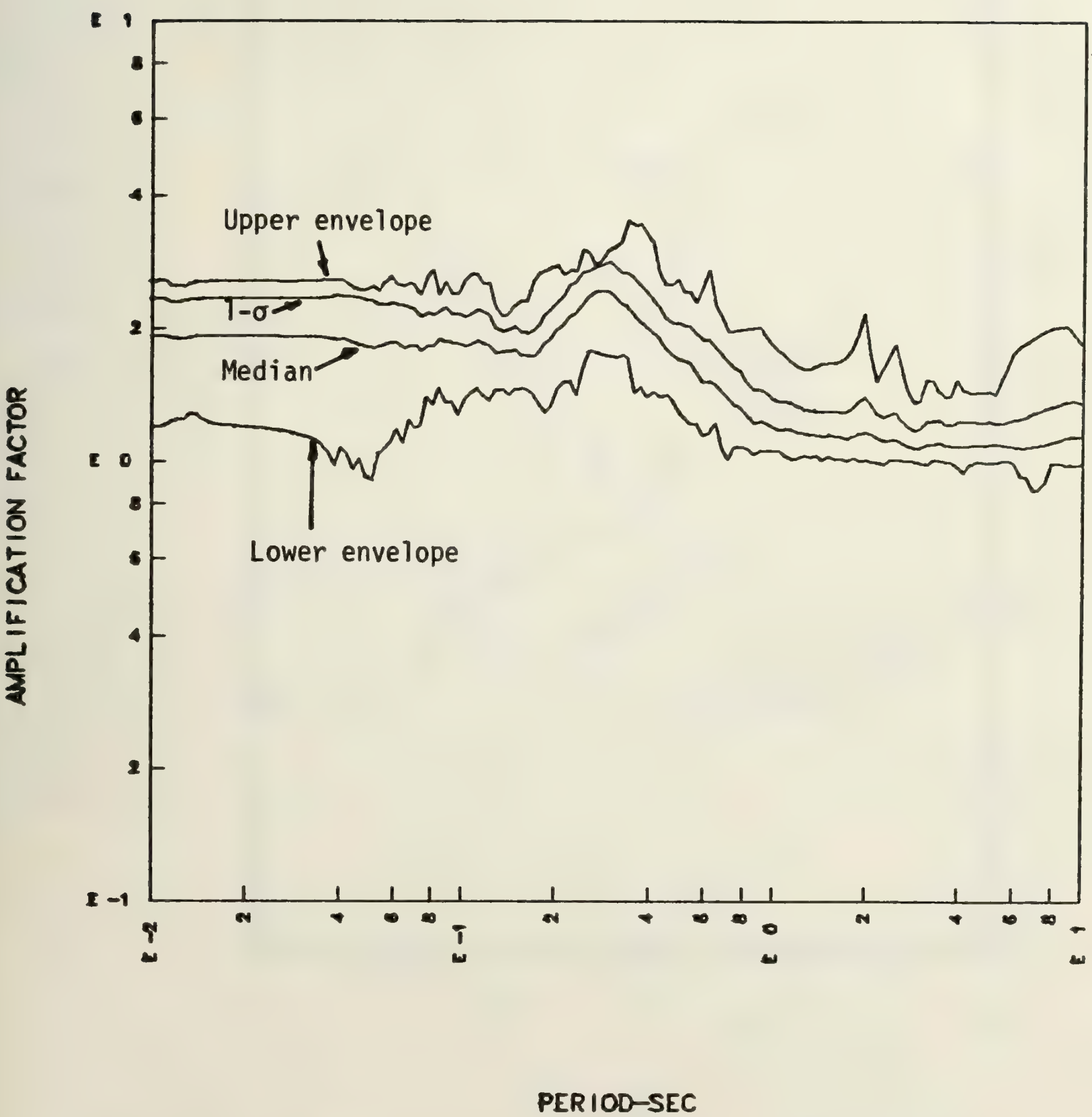


Fig. 5.4.3. Uncertainty of the "Site Specific Amplification Factors" for a IIb sand-like site.

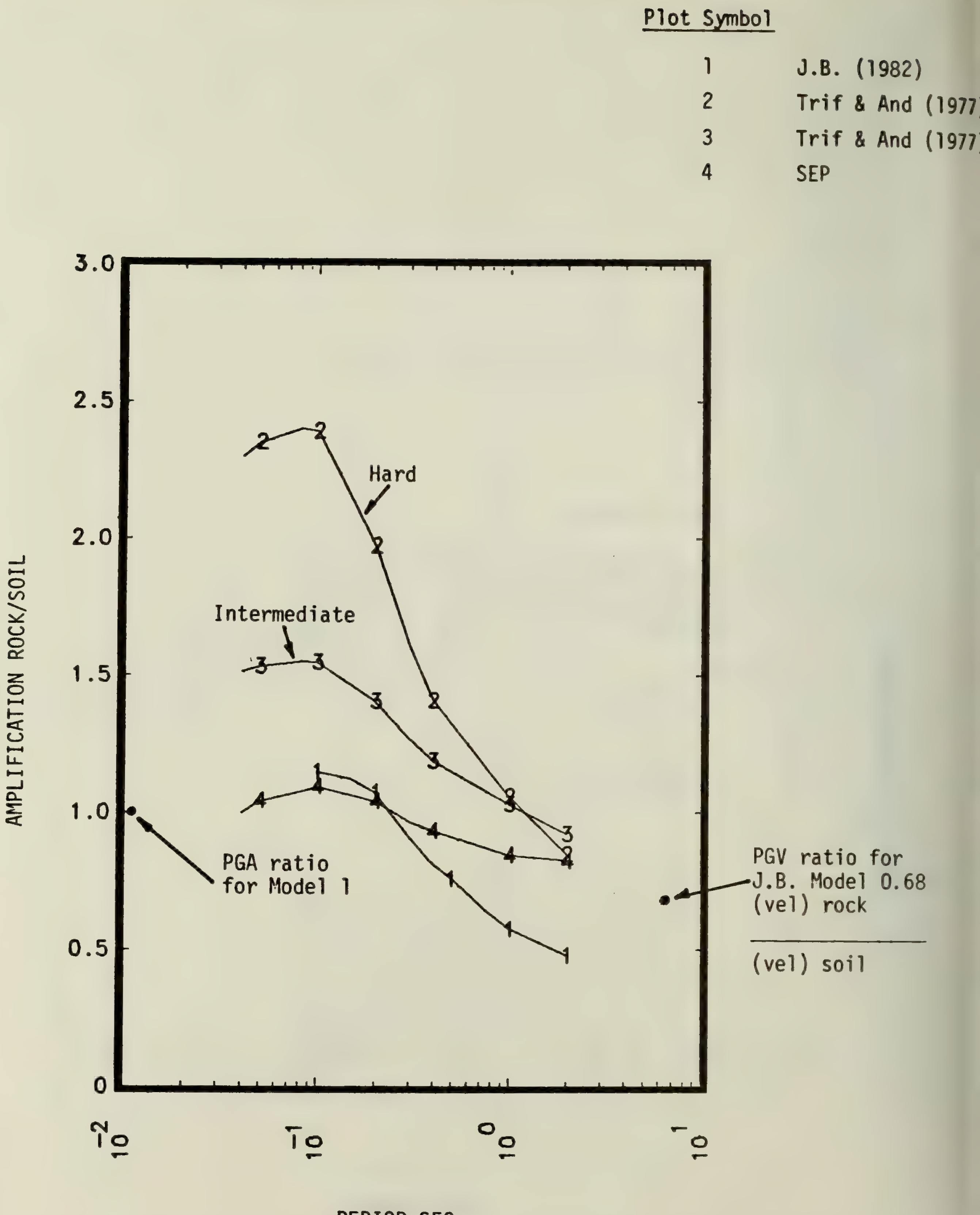


Fig. 5.7.1. Simple correction factors obtained by regression analysis of WUS data "Fall Back" model is the J.B. Model plot symbol 1.

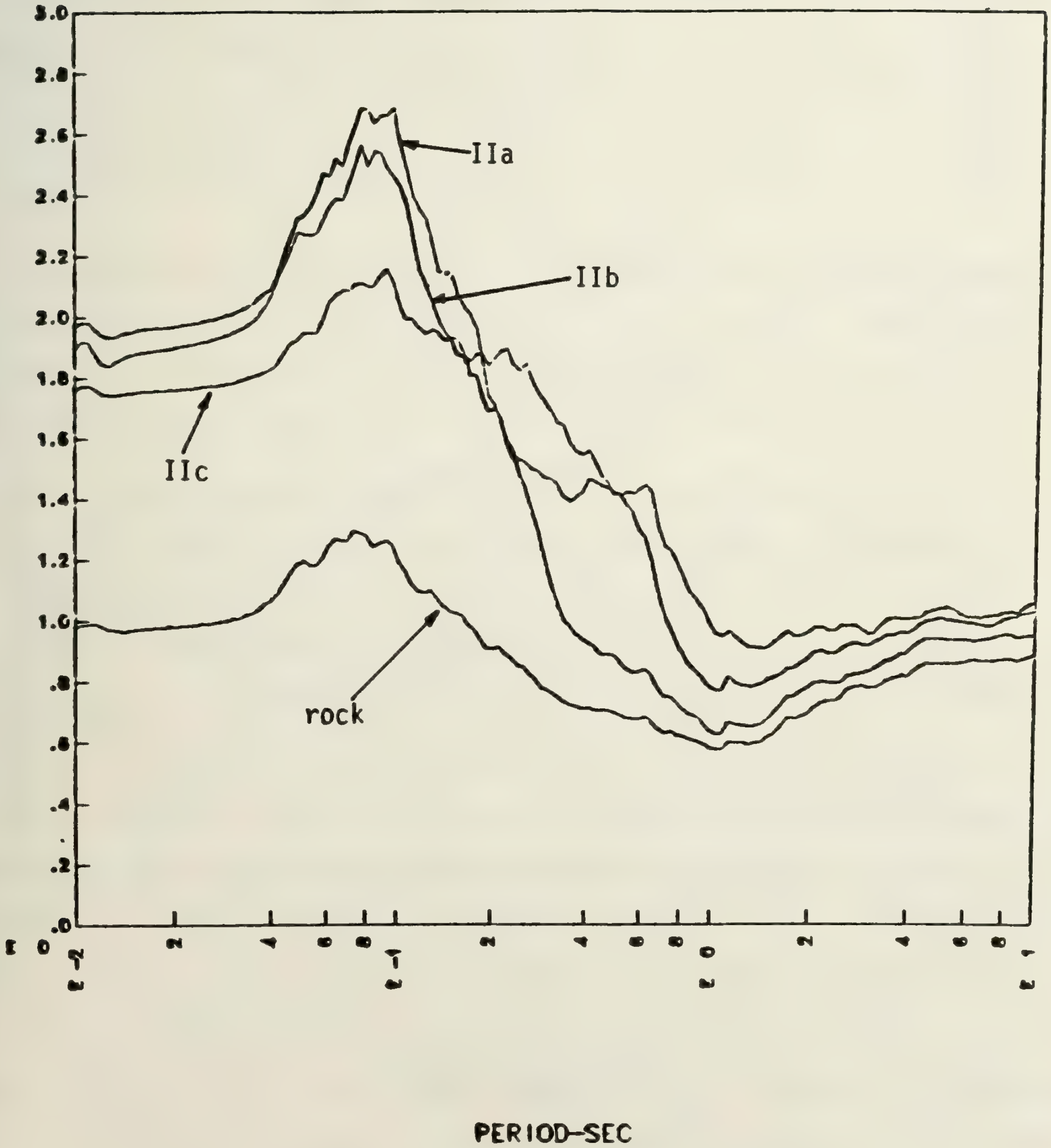


Fig. 5.7.2a. Proposed median correction factors (site/soil) for sand-like categories. Rock/soil shown for reference.

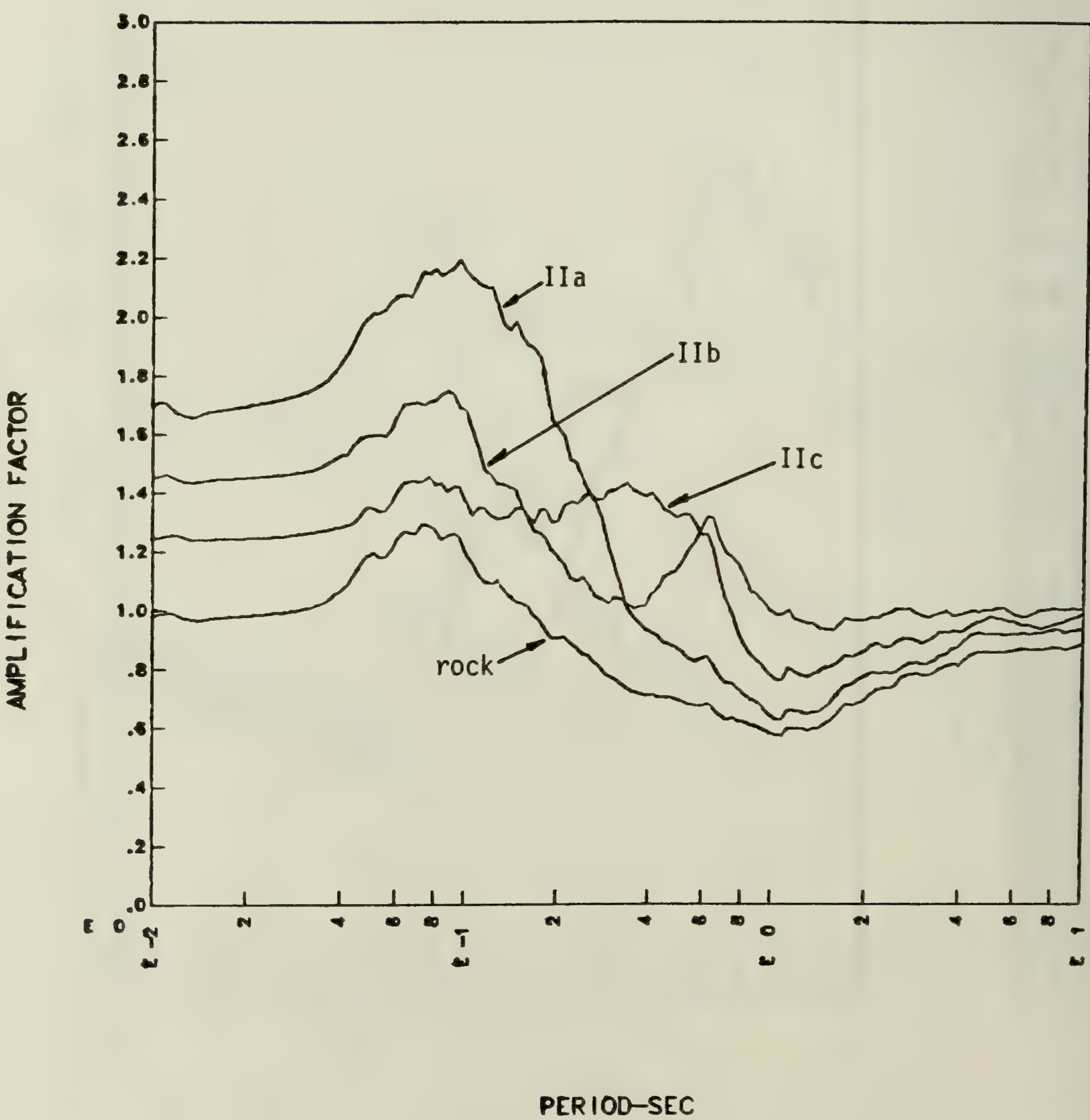


Fig. 5.7.2b. Proposed median correction factors (site/soil) for till-like categories.

6. Questionnaire Q6

6.1 Ground Motion Models

Tables 6.1a, 6.2a and 6.3a are a listing of the ground motion models for acceleration, velocity and spectra which will be considered for use in the EUS Seismicity Characterization Project. They were developed from your responses to the previous questionnaire (Q4) and your input after the Feedback meeting on June 27, 1984. For your convenience, Tables, 6.1b, 6.2b and 6.3b summarize our (LLNL's) interpretation of your answers to Q4. Although the models have been partitioned into groups, this is done only for your convenience in identifying the models with the discussion in Q4. We will not be asking you to weigh the 7 (6 for spectra) different classes of models as was done in Q4.

In Question 6.1 you are requested to indicate your choices of models to be used in the analysis, by filling Tables 6.1, 6.2, and 6.3. These tables contain eight vertical columns to distinguish between the four regions and the two scales (M_{bLg}, MMI). In each of the eight columns please select:

- o a best estimate model
- o a subset of the models with associated levels of confidence

The best estimate model, the model to which you associate highest confidence, should represent that model which you believe best represents the average ground motion at a site. Even if you believe there is no one best model but there are several comparable models, it is still necessary for you to select one model which can be used in the "best estimate" hazard analyses. Since many models have been developed based on a variety of criteria, e.g. different data sets, different parameters, you may believe that more than one model can provide useful estimates of the ground motion. Thus, you are requested to select a subset of the models from the list of models in Tables 6.1, 6.2, and 6.3 (up to seven models in Tables 6.1 and 6.2 and up to six models in Table 6.3). These models represent your uncertainty in estimating

the expected value of ground motion at a site given the magnitude of the source and the source to site distance. You are requested to associate a "level of confidence" to each model. Your level of confidence should be based on your opinion of the data and methods used to develop the model, the ability of the model to accurately reflect the attenuation and ground motion within a region, and any other information you deem appropriate to judge the models.

When selecting the models please keep in mind their application in the hazard analysis for this project. Specifically, it should be recognized that (1) earthquakes are assumed to be point sources and distance is treated as epicentral distance, (2) although the seismicity panel members have revised their inputs so that the highest upper magnitude cutoff is not higher than the saturation value on the magnitude (approximately 7.5 m_{bLg}), the ground motion models will be assumed to be applicable over the entire range of magnitudes, 3.75-7.5 m_{bLg}, and (3) depending on your recommendations for adjusting for local site effects, the ground motion models will be adjusted for local site effects as follows:

- o since the largest portion of the data used to develop the ground motion models is for generic soil, we chose that to be the base case. Hence, in order to retain consistency between all models, for the ground motion models which distinguish between several site types, the base case will be the soil version.

- o the appropriate local site effect correction (depending on your choice of methods of correction) will be applied for sites with other soil conditions than the base case.

Question 6.1

For the 3 ground motion parameters, acceleration, velocity and spectra, please select 8 sets (4 regions and 2 magnitude scales) of models in Tables 6.1a, 6.2a, and 6.3a respectively by:

- o selecting a best estimate model and entering the model code, e.g. A5-G21 or G51, in the boxes at the bottom of the table.

- o assigning a level of confidence to at most 7 models (6 for spectra) per column; enter the level in the appropriate boxes in each of the 8 columns. The sum of the levels of confidence within a column must add to 1.

Please fill Table 6.1c if you selected any model requiring the knowledge of an undetermined parameter such as γ of Model D13.

Table 6.1a: Ground Motion Acceleration Models

Class of Models	File Index	Model	For Use with Magnitude				For Use with MMI			
			NE	SE	NC	SC	NE	SE	NC	SC
1 Intensity No-Weighting	8	A1-G16[a]								
	1	A3-G15								
	12	A3-G16[d,a]								
	4	A4-G12								
	16	A4-G16[a]								
	20	A5-G16[a]								
2 Intensity Distance-Weighting	9	A1-G21								
	30	A1-G22[b]								
	13	A3-G21								
	32	A3-G22[b]								
	17	A4-G21								
	31	A4-G22[b]								
	21	A5-G21								
	29	A5-G22[b]								
3 Intensity Magnitude Weighting	10	A1-G31								
	3	A3-G31								
	18	A4-G31								
	22	A5-G31								
4 Intensity Magnitude Distance Weighting	11	A1-G41								
	15	A3-G41								
	19	A4-G41								
	23	A5-G41								
5 Semi-empirical	28	G51								
	24	G52								
	5	G53								

Table 6.1a: Ground Motion Acceleration Models (continued)

6	6	D12								
Direct-1	25	D13[c]								
	26	D14								
7	7	D21								
Direct-2		D22[e]								
Best Estimate Model:										

Notes: (a) These models have a basement rock, sedimentary rock and soil form. See Table 5.3.1, Trifunac (1976a) entry. (The base case being soil)

(b) These models have a medium site and soft site form. See discussion in Section 5.3.3. (The base case being soft)

(c) For this model the measure of distance is the closest distance to the fault rupture.

(d) The "Trifunac-Anderson" model labeled #27 (A6-G16) in interim report NUREG/GR 3756, has been updated after the feedback meeting and is now identical to model number 12 (A3-G16). It now uses the "Modified Gupta-Nuttli" equation A3 instead of the original equation, i.e. the leading coefficient is 3.2 in lieu of 3.7. So the new symbol becomes A3-G16 instead of A6-G16.

(e) This model was added after the feedback meeting of June 27, 1984. It was developed by G. Atkinson and a full description can be found in the appended paper recently submitted for publication to BSSA.

If your response is the same for all 4 regions you need only fill out one column for each of the 2 magnitude scales.

If you have chosen a model which contains an unspecified term γ, please provide the value below.

Table 6.1c

Model Code	Value of γ
D13 file index 25	

Table 6.2a: Ground Motion Velocity Models

Class of Models	File Index	Model	For Use with Magnitude				For Use with MMI			
			NE	SE	NC	SC	NE	SE	NC	SC
1 Intensity No-Weighting	38	A1-GV12[a]								
	33	A3-GV12[a]								
	44	A4-GV12[a]								
	47	A5-GV12[a]								
2 Intensity Distance-Weighting	34	A3-GV12[a]								
	39	A1-GC22[b]								
	42	A3-GV22[b]								
	45	A4-GV22[b]								
	48	A5-GV22[b]								
3 Intensity Magnitude Weighting	40	A1-GV31								
	35	A3-GV31								
	46	A4-GV31								
	49	A5-GV31								
5 Semi-empirical	50	GV51								
	36	GV52								
	52	GV53								
6 Direct-1	51	DV12								
7 Direct-2	37	DV21								
Best Estimate Model:										

Notes: (a) These models have a basement rock, sedimentary rock and soil versions. (The base case being soil)

(b) These models have a medium and soft versions. (The base case being soft)

Table 6.3a Ground Motion Spectra Models

Model Class	File Index	Anchor Equation Acceleration and/or Velocity	For Use with Magnitude				For Use with Intensity			
			NE	SE	NC	SC	NE	SE	NC	SC
RS1 (RG 1.60)	161	G51								
	170	G52								
	179	G53								
	80	D13								
	71	D21								
RS2 (NBS, 1978 ATC)	134	G51								
	143	G52								
	152	G53								
	98	D13								
	89	D21								
RS3 (Newmark-Hall)	188	G51/GV51								
	197	G52/GV52								
	206	G53/GV53								
	116	D13/DV21								
	107	D21/DV21								
RS4 Dist.Weight	53	SEP1 Bernreuter								
RS5 Mag. Weight	62	SEP2 Bernreuter								
RS6 No Weight	125	Trifunac-Anderson								
Best Estimate Model:										

Notes: (a) Models 53 and 62 have a soil and rock versions. See Figure 5.3.1a Plot Symbol 4.

(b) Model 125 has a hard rock, intermediate and deep soil versions. See Figure 5.3.1a Plot Symbols 2 & 3.

6.2 Ground Motion Saturation

For this project, the hazard analysis has been based on modeling the ground motion parameter, given magnitude (and/or intensity) and distance, as having a lognormal distribution, i.e. as having an unbounded range. At the feedback meeting some of you indicated that a more appropriate model would be one which restricted the ground motion parameter (GMP) to a finite range. To accomodate this view we propose to include a model for your consideration, a model for the GMP that has a truncated lognormal distribution. To do this it is necessary to specify an upper limit to the range of the GMP's.

Any upper limit on the range of the GMP's should be based on some interpretation of ground motion saturation. Three interpretations of saturation are proposed (Note: the discussion is given in terms of acceleration although a similar discussion holds for velocity and spectra):

- Type I: There is an absolute maximum acceleration, independent of magnitude and distance, which will not be exceeded.
- Type II: The maximum acceleration is a function of magnitude and distance; this will be modeled by assuming the maximum acceleration is a fixed number of standard deviation from the mean in the lognormal distribution of the GMP's.
- Type III: For any magnitude and distance the maximum acceleration is the minimum of an absolute maximum and a fixed number of standard deviations from the mean; this is an envelope of Type I and II saturation.

The 3 types of limits, drawn as a function of distance R for a fixed magnitude m are depicted in Figure 6.1:

- Type I, an absolute maximum acceleration, a_1, results in the horizontal curve C_1
- Type II, the maximum acceleration is a fixed number, n, of standard deviations from the mean, thus the limit curve is C_2 which "parallels" the mean curve, a(m, R)
- Type III, the envelope of Type I and II, results in the curve C_3

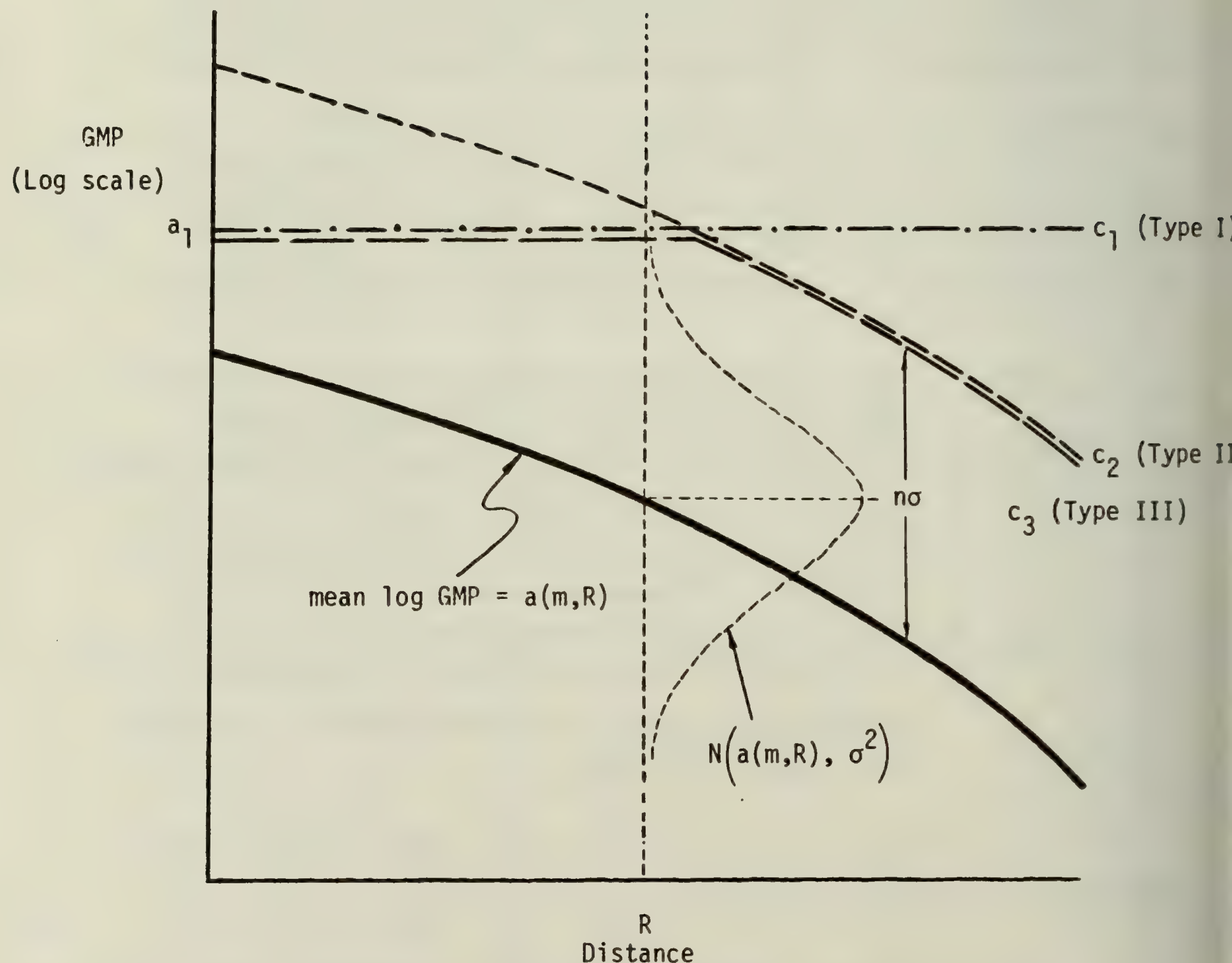


Fig. 6.1 Saturation

Description of the three types of models considered for the physical saturation of the ground motion. The random variation of the logarithm of the GMP is modeled by a normal distribution with mean a(m,R) and standard deviation $\tilde{\sigma}$

We would like you to consider the potential physical saturation of the ground motion parameters and, if the ground motion parameters do saturate, the most appropriate way to model physical saturation. Please recognize that we will continue to assume that, given magnitude and distance, the GMP basically has a lognormal distribution. If the GMP does saturate, bounding the range implies that the distribution of the GMP will be modeled as a truncated lognormal distribution, truncated at the upper limit. The 3 types of saturations are different methods for modeling the upper limit.

Question 6.2

Using Table 6.4 please indicate the method you consider most appropriate for modeling the range of values for each of the ground motion parameters, acceleration, velocity and spectra. Indicate your choice by writing a check mark (✓) by the appropriate method for each ground motion parameter.

Table 6.4

Method for Describing Range of GMP	Ground Motion Parameter		
	Acceleration	Velocity	Spectra
1. GMP is not bounded; range is $(0,\infty)$			
2. GMP saturates; maximum is best described by a Type I limit.			
3. GMP saturates; maximum is best described by a Type II limit			
4. GMP saturates; maximum is best described by a Type III limit			

If you have checked method 1, no bound, in Question 6.2 for all three GMP's, please skip Question 6.3 and go to Question 6.4.

If you selected method 2, 3 or 4 it is necessary to specify the parameters, i.e. a_1 or n, which characterize the upper limit. We would like you to specify a best estimate value for the appropriate parameter.

Question 6.3

In Table 6.5 please give your best estimate for the parameter(s) which characterize the method you choose for describing the upper limit of the GMP's of the range of each of the GMP's.

Table 6.5

	Ground Motion Parameter		
	Acceleration	Velocity	Spectra
Absolute Maximum, a_1 (Needed for method 2 & 4) (cm/s/s, cm/s, cm/s)			
Number of Standard Deviations, n (needed for method 3 & 4, n, not necessarily an integer)			

6.3 Random Variation

The hazard analysis used to construct a seismic hazard curve or a uniform hazard spectra at a site is based on assuming that, given a source magnitude (and/or intensity) and source to site distance, the GMP is a random variable. As indicated earlier, for this project, random variation in the GMP will be modeled by the lognormal (or truncated lognormal) distribution. It is recognized, per the discussion at the feedback meeting, that the unbounded lognormal distribution may not be the optimal model for describing the variation in the GMP given magnitude and distance. However, given that there is only limited information in the literature regarding alternative distributions we consider it appropriate to continue to use the lognormal distribution in the hazard analyses for this project. In addition, allowing truncated lognormal distributions as alternative models introduces some flexibility which, we believe, will provide models which are more concentrated about the central value of the distribution--the characteristic observed in some plots of historical data.

An important characteristic of the lognormal distribution, in addition to the description of the mean (of the log GMP) given by the ground motion model, is the measure of the random variation in the GMP. This is usually described by σ, the standard deviation of the log GMP.

Although we asked you to provide best estimates and uncertainty bounds, we believe it is appropriate to have you reconsider your estimates of the random variation you provided in responding to Questionnaire 4, in light of what you have learned about the way LLNL uses the ground motion models in the hazard analysis, the possibility (if you indicate it is appropriate) of making local site effect corrections, or any new developments in the field of ground motion,

When assessing the value of σ there are several points which we believe you should consider:

- o Many of the ground motion models are based on fitting empirical models to historical data. An estimate of the "standard deviation of the error" is a common output of the fitting process. One might consider this to be a reasonable estimate of σ. However, it should be recognized that the standard deviation of the error potentially consists of 2 components of variance -- the random variation in the GMP about its expected or average value (as estimated by the ground motion model) and the adequacy of the specific model in describing the true expected or average value of the GMP. It is important in doing the hazard analysis that only the random variation component be considered in making the probability calculations.

- o What, if any, effect will correcting for local site conditions have on the level of random variation? It should be recognized that adjustments will be made, at your discretion, in the ground motion models for different types of conditions at the site. If making such adjustments will have an effect on the level of random variation, this should be recognized in assessing your estimates of σ.

- The hazard analysis assumes that the GMP random variation is independent of magnitude and distance as well as the site, although regional variation in σ is considered, and some implicit dependence on the distance may be introduced if you choose Type II or Type III saturation as an answer to Question 6.2.

- Overall, given an earthquake of a fixed magnitude and distance from the site, the GMP at the site will be affected by many factors including (1) the frequency content and other characteristics unique to each earthquake, (2) the specific travel path of the ground motion and (3) the unique soil conditions of the specific site, even if a local site correction is made -- the correction will only be made for a soil class, not for each specific site.

Question 6.4

Using Table 6.6 for each GMP and each of the 4 regions, update, if necessary, your

- best estimate of σ
- estimate of the interval which you believe, with a high degree of confidence, represents the possible range of σ

Table 6.6
(Please give values of σ to be used with natural logarithm)

Ground Motion Parameter:		Region: Northeast	Southeast	North Central	South Central
PGA	Best Estimate:				
	Uncertainty Bounds:				
PGV	Best Estimate:				
	Uncertainty Bounds:				
Spectra	Best Estimate:				
	Uncertainty Bounds:				

6.4 Correction for Local Site Effects

Most ground motion models are based on historical records from various sites involving various soil types and depths of soil. The local site soil conditions are known to have a significant effect on the ground motion parameters and spectra. This local site effect may not be very well represented by the ground motion models in our catalogue. Thus, it may be appropriate to make some correction for local site effects to realistically estimate the seismic hazard curves and uniform hazard spectra for any site.

We would like your opinion regarding:

- the significance of the local site effect
- the quality of some alternative methods for "correcting" for local site effects (You may want to review Section 5.7 for added background on this matter.)

Question 6.5

Noting that most of the GM models used in the analysis are for generic soil, for each of the GMP's please indicate in Table 6.7, on a scale of 0-10 (10 being high), how important you think it is to consider the soil conditions at the site when modeling the expected or average value of the GMP's at the site, i.e. how important is it to adjust the models in Tables 6.1a, 6.2a and 6.3a for soil types other than the base case (i.e. other than "generic soil").

Table 6.7

Ground Motion Parameter	Importance to Consider Correction	
	Eastern Rock	Shallow Soil
Acceleration		
Velocity		
Spectra		

At the feedback meeting and in Section 5 of this Questionnaire, three methods of adjusting (correcting) the ground motion models for different types of site conditions were discussed. One method, referred to as a "simple correction", involves making a deterministic adjustment. The second method, referred to as a "categorical correction" is based on more sophisticated analysis of the GMP's for a sample of earthquake time histories and sites. The third method referred to as a "site specific correction" (see Sections 5.4 and 5.5) involves an extensive analysis for each site, addressing a number of site specific factors.

Question 6.6

Using Table 6.8, rank the four alternatives on a 0-10 scale with 0 representing a nonviable approximation and 10 meaning that the alternative would be the most desirable method.

Table 6.8

Method of Adjustment		Ground Motion Parameter		
Index	Type	Acceleration	Velocity	Spectra
1	No correction			
2	Simple correction			
3	Categorical correction			
4	Site specific correction			

Since site specific analysis is not part of the present scope of this project, we need to elicit your opinion as to what weight you would assign to the first 3 methods of Table 6.8, as described in Section 5.7. The simple correction we will use will only have two types of sites, Rock - Soil. We will use the correction factor developed by Joyer & Boore, USGS open file report 82-977, unless you prefer to give us another set of correction factors, for example, Fig. 5.3.1a of this document. (We need one factor for PGA and one factor for each frequency.)

In answering question 6.7, please keep in mind, as discussed in Section 5.5, that generally the dominant contributors to the hazard are the earthquakes occuring within less than 100 km from the site (relative importance of surface versus body waves).

Question 6.7

When filling in Table 6.9, you may choose one of the three methods exclusively by assigning a level of confidence of 1.0 to only one of them, or you may recommend using more than one method by assigning levels of confidence lower than 1.0, but adding to unity. In the latter case, the best estimate will be based on using the method with the highest level of confidence whereas the uncertainty analysis will be based on randomizing between the selected methods. And to avoid any ambiguity by possibly having several equal highest levels of confidence, please fill the bottom box to indicate your best estimate.

Table 6.9

Methods of Adjustment		Ground Motion Parameter		
Index	Type	Acceleration	Velocity	Spectra
1	No correction			
2	Simple correction			
3	Categorical correction			
Your Best estimate method (Please indicate 1, 2 or 3				

Question 6.8

In Section 5 we outlined an approach to correct for local site effects. At the feedback meeting it was suggested that our approach was too simple and that other factors should be included in the assessment. Given the current state-of-the-art and the fact that for most sites/ground motion model combinations the main contribution to the seismic hazard is coming from earthquakes within less than 100 km of the site, please indicate below in Table 6.10 what factors should be considered in a site specific analysis and indicate their relative level of importance.

Table 6.10	
Factors influencing site effects	
Factor	Comments

6.5 Self Rating

In the previous questionnaire (Q4) you were asked to indicate your level of expertise with regard to assessing the utility of the ground motion models. In light of the discussion at the feedback meeting and recognition that local site conditions should be considered in modeling the GMP's, it has been necessary to elicit your opinions on a broader range of topics in this questionnaire (Q6). Thus, it is necessary to ask you to reconsider your self-rate. It is recognized that it may be most appropriate to have you self-rate yourself on the different topics, e.g. utility of the ground motion models and local site effects, however, this is not possible in the context of the methodology developed to combine the hazard analyses based on the opinions of the different members of the seismicity and ground motion panels. Thus, we must ask you to consider your overall expertise about all issues raised in the previous questionnaire (Q4) and the present questionnaire (Q6) in your self-rate.

Question 6.9

Please indicate your level of expertise, relative to the scientific community at large, with regard to the several issues for which your opinions have been elicited. Please use a scale of 0 to 10, with 10 indicating a "high" level of expertise.

Level of expertise:____________________

TABLE A.1

EQUATIONS FOR THE GROUND MOTION MODELS USED IN THE ANALYSIS
INCLUDES THE INPUT FROM THE 5 GROUND MOTION EXPERTS

***** ROCK *****

JUNE 1, 1984

THE EQUATIONS 1 THROUGH 32 ARE PEAK GROUND ACCELERATION ATTENUATION MODELS
THE EQUATIONS 33 THROUGH 52 ARE PEAK GROUND VELOCITY ATTENUATION MODELS
THE EQUATIONS 53 THROUGH 214 ARE PSEUDO RELATIVE VELOCITY, 5% DAMPED
SPECTRAL ATTENUATION MODELS.
EACH SPECTRAL MODEL ACTUALLY COMPRISES 9 EQUATIONS. ONE FOR EACH OF THE
NINE FRAQUENCIES, WHICH ARE:
0.5, 1.0, 2.5, 3.3, 5.0, 10.0, 12.5, 20.0 AND 25.0 HZ.
FOR EXAMPLE THE SPECTRAL MODEL NUMBER 89 ACTUALLY COMPRISES THE EQUATIONS
NUMBER 89 THROUGH 97, THE EQUATION 89 BEING FOR THE 0.5 HZ FREQUENCY,AND
THE EQUATION NUMBER 97 BEING FOR THE 24.0 HZ FREQUENCY.

ACCELERATION CALCULATED WITH THESE MODELS IS IN CM/S/S
VELOCITY .... CM/S
PSEUDO RELATIVE VELOCITY .... CM/S

1 EQUATION *** A3 - G15 ***				15.0	999.0	1.1	.1
2.43000	0.00000	0.00000	.58000	-.00064	-.68000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
2 EQUATION *** A3 - G21 ***				15.0	999.0	1.1	.1
3.61000	0.00000	0.00000	.57000	-.00063	-.99000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
3 EQUATION *** A3 - G31 ***				15.0	999.0	1.1	.1
2.98000	0.00000	-.13000	.63000	-.00069	-.74000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
4 EQUATION *** A4 - G12 ***				0.0	999.0	1.1	.1
-1.99000	0.00000	0.00000	.96000	-.00442	-.30000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
5 EQUATION *** G53 ***				0.0	999.0	2.1	.1
1.47000	1.10000	0.00000	-.00170	-.88000	0.00000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
6 EQUATION *** D12 ***				0.0	5.6	2.1	.1
4.66000	.94000	0.00000	-.02200	-1.27000	25.70000	.00470	-.00029
1.48000	1.51000	0.00000	-.04100	-1.27000	25.70000	.01080	-.00075
7 EQUATION *** D21 ***				0.0	4.4	3.1	.1
3.89000	.57600	-.00281	-.41700	1.30100	-4.37100	0.00000	0.00000
1.34000	1.15000	-.00281	-.41700	2.10000	-7.96800	0.00000	0.00000
8 EQUATION *** A1 - G16 ***				10.0	999.0	1.1	.1
1.73000	0.00000	0.00000	.67000	-.00035	-.84000	0.00000	.66000
0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
9 EQUATION *** A1 - G21 ***				10.0	999.0	1.1	.1
3.43000	0.00000	0.00000	.57000	-.00030	-1.04000	0.00000	0.00000

```
  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
10    EQUATION   *** A1 - G31 ***                  10.0     999.0       1.1        .1
  2.77000   0.00000   -.13000    .63000   -.00033   -.79000   0.00000   0.00000
  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
11    EQUATION   *** A1 - G41 ***                  10.0     999.0       1.1        .1
  2.30000   0.00000    .55000    .32000   -.00017  -1.08000   0.00000   0.00000
  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
12    EQUATION   *** A3 - G16 ***                  15.0     999.0       1.1        .1
  1.95000   0.00000   0.00000    .67000   -.00074   -.78000   0.00000    .66000
  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
13    EQUATION   *** A3 - G21 ***                  15.0     999.0       1.1        .1
  3.61000   0.00000   0.00000    .57000   -.00063   -.99000   0.00000   0.00000
  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
14    EQUATION   *** A3 - G31 ***                  15.0     999.0       1.1        .1
  2.98000   0.00000   -.13000    .63000   -.00069   -.74000   0.00000   0.00000
  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
15    EQUATION   *** A3 - G41 ***                  15.0     999.0       1.1        .1
  2.40000   0.00000    .55000    .32000   -.00035  -1.05000   0.00000   0.00000
  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
16    EQUATION   *** A4 - G16 ***                   0.0     999.0       1.1        .1
   .04500   0.00000   0.00000    .67000   -.00308   -.21000   0.00000    .66000
  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
17    EQUATION   *** A4 - G21 ***                   0.0     999.0       1.1        .1
  1.99000   0.00000   0.00000    .57000   -.00262   -.50000   0.00000   0.00000
  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
18    EQUATION   *** A4 - G31 ***                   0.0     999.0       1.1        .1
  1.18000   0.00000   -.13000    .63000   -.00290   -.20000   0.00000   0.00000
  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
19    EQUATION   *** A4 - G41 ***                   0.0     999.0       1.1        .1
  1.49000   0.00000    .55000    .32000   -.00147   -.78000   0.00000   0.00000
  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
20    EQUATION   *** A5 - G16 ***                   0.0     999.0       1.1        .1
   .11000   0.00000   0.00000    .67000   -.00268   -.45000   0.00000    .66000
  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
21    EQUATION   *** A5 - G21 ***                   0.0     999.0       1.1        .1
  2.04000   0.00000   0.00000    .57000   -.00228   -.70000   0.00000   0.00000
  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
22    EQUATION   *** A5 - G31 ***                  15.0     999.0       1.1        .1
  1.24000   0.00000   -.13000    .63000   -.00252   -.42000   0.00000   0.00000
  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
23    EQUATION   *** A5 - G41 ***                   0.0     999.0       1.1        .1
  1.55000   0.00000    .55000    .32000   -.00128   -.89000   0.00000   0.00000
  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
24    EQUATION   ***   G52   ***                  15.0     999.0       5.1        .1
  1.47000   0.00000   1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
25    EQUATION   ***   D13   ***                   0.0       5.6       4.1        .1
  2.83900    .79250   -.00200   -.79700    .01200    .91600    .26940   0.00000
   .14630   1.27430   -.00200   -.79700    .01200   1.47300  -2.83800   0.00000
26    EQUATION   ***   D14   ***                   0.0     999.0       1.1        .1
  1.48100   1.15000   0.00000   0.00000   -.01360   -.83300    .00172   0.00000
  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
27   *** TRIFUNAC-ANDERSON                         20.0     999.0       1.1        .1
  2.29000   0.00000   0.00000    .67000   -.00074   -.78400   0.00000    .66000
  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
28    EQUATION   ***   G51   ***                   0.0     999.0       2.1        .1
  3.16000   1.24000   0.00000   0.00000  -1.24000  25.00000   0.00000   0.00000
  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
29    EQUATION   *** A5 - G22 ***                   0.0     999.0       1.1        .1
  1.75000   0.00000   0.00000    .68000   -.00272   -.81500   0.00000   0.00000
```

```
 0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
30  EQUATION  *** A1 - G22 ***                  10.0      999.0        1.1         .1
 3.40100   0.00000    0.00000     .68000    -.00035   -1.20900    0.00000    0.00000
 0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
31  EQUATION  *** A4 - G22 ***                   0.0      999.0        1.1         .1
 1.68800   0.00000    0.00000     .68000    -.00313    -.57000    0.00000    0.00000
 0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
32  EQUATION  *** A3 - G22 ***                  15.0      999.0        1.1         .1
 3.62600   0.00000    0.00000     .68000    -.00075   -1.15500    0.00000    0.00000
 0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
33  EQUATION  *** A3 - GV12 ***                 15.0      999.0        1.1         .1
 -.11000   0.00000    0.00000     .67000    -.00074    -.78000    0.00000    0.00000
 0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
34  EQUATION  *** A3 - GV21 ***                 15.0      999.0        1.1         .1
 -.51000   0.00000    0.00000     .76000    -.00084    -.83000    0.00000    0.00000
 0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
35  EQUATION  *** A3 - GV31 ***                 15.0      999.0        1.1         .1
 -.99000   0.00000     .17000     .51000    -.00056    -.60000    0.00000    0.00000
 0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
36  EQUATION  ***  GV52  ***                     0.0      999.0        1.1         .1
 -.92400    .95000    0.00000    0.00000    -.00230    -.76500    0.00000    0.00000
 0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
37  EQUATION  ***  DV21  ***                     0.0        4.4        3.1         .1
-3.11000   1.15000    -.00122    -.42000    1.30000   -4.37000    1.00000    0.00000
-8.29000   2.30000    -.00122    -.42000    2.10000   -7.97000    1.00000    0.00000
38  EQUATION  *** A1 - GV12 ***                 10.0      999.0        1.1         .1
 -.33000   0.00000    0.00000     .67000    -.00035    -.84000    0.00000    0.00000
 0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
39  EQUATION  *** A1 - GV22 ***                 10.0      999.0        1.1         .1
 -.97000   0.00000    0.00000     .92000    -.00048   -1.21000    0.00000    0.00000
 0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
40  EQUATION  *** A1 - GV31 ***                 10.0      999.0        1.1         .1
-1.16000   0.00000     .17000     .51000    -.00027    -.64000    0.00000    0.00000
 0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
41  EQUATION  *** A3 - GV12 ***                 15.0      999.0        1.1         .1
 -.11000   0.00000    0.00000     .67000    -.00074    -.78000    0.00000    0.00000
 0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
42  EQUATION  *** A3 - GV22 ***                 15.0      999.0        1.1         .1
 -.67000   0.00000    0.00000     .92000    -.00101   -1.14000    0.00000    0.00000
 0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
43  EQUATION  *** A3 - GV31 ***                 15.0      999.0        1.1         .1
 -.99000   0.00000     .17000     .51000    -.00056    -.60000    0.00000    0.00000
 0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
44  EQUATION  *** A4 - GV12 ***                  0.0      999.0        1.1         .1
-2.02000   0.00000    0.00000     .67000    -.00310    -.21000    0.00000     .09600
 0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
45  EQUATION  *** A4 - GV22 ***                  0.0      999.0        1.1         .1
-3.29000   0.00000    0.00000     .92000    -.00420    -.35000    0.00000    0.00000
 0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
46  EQUATION  *** A4 - GV31 ***                  0.0      999.0        1.1         .1
-2.44000   0.00000     .17000     .51000    -.00230    -.16000    0.00000    0.00000
 0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
47  EQUATION  *** A5 - GV12 ***                  0.0      999.0        1.1         .1
-1.95000   0.00000    0.00000     .67000    -.00270    -.45000    0.00000     .09600
 0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
48  EQUATION  *** A5 - GV22 ***                  0.0      999.0        1.1         .1
-3.20000   0.00000    0.00000     .92000    -.00370    -.61000    0.00000    0.00000
 0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
49  EQUATION  *** A5 - GV31 ***                 15.0      999.0        1.1         .1
-2.40000   0.00000     .17000     .51000    -.00200    -.34000    0.00000    0.00000
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   0.00000   0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
50    EQUATION   ***   GV51   ***                  15.0      999.0        1.1         .1
  -6.72000   2.30000   0.00000    0.00000    0.00000   -1.00000    0.00000    0.00000
   0.00000   0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
51    EQUATION   ***   DV12   ***                   0.0      999.0        1.1         .1
  -7.86000   2.30000   0.00000    0.00000    -.00760    -.84000     .00099    0.00000
   0.00000   0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
52    EQUATION   ***   GV53   ***                   0.0      999.0        1.1         .1
  -5.38000   1.70000   0.00000    0.00000    -.00100    -.75600    0.00000    0.00000
   0.00000   0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
53    EQUATION 127,*** MODEL 123 ***                 15.0      999.0        1.1         .1
  -4.52770   0.00000   0.00000     .88600    -.00410     .06100    0.00000    0.00000
   0.00000   0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
54    EQUATION 126,*** MODEL 122 ***                 15.0      999.0        1.1         .1
  -3.21700   0.00000   0.00000     .81600    -.00380    -.10000    0.00000    0.00000
   0.00000   0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
55    EQUATION 125,*** MODEL 121 ***                 15.0      999.0        1.1         .1
  -1.22300   0.00000   0.00000     .65000    -.00300    -.34600    0.00000    0.00000
   0.00000   0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
56    EQUATION 124,*** MODEL 120 ***                 15.0      999.0        1.1         .1
   -.79980   0.00000   0.00000     .62000    -.00280    -.43300    0.00000    0.00000
   0.00000   0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
57    EQUATION 123,*** MODEL 119 ***                 15.0      999.0        1.1         .1
   -.53830   0.00000   0.00000     .56000    -.00260    -.48700    0.00000    0.00000
   0.00000   0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
58    EQUATION 122,*** MODEL 118 ***                 15.0      999.0        1.1         .1
  -1.07140   0.00000   0.00000     .56000    -.00250    -.60500    0.00000    0.00000
   0.00000   0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
59    EQUATION 121,*** MODEL 117 ***                 15.0      999.0        1.1         .1
  -1.45000   0.00000   0.00000     .56000    -.00260    -.61200    0.00000    0.00000
   0.00000   0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
60    EQUATION 120,*** MODEL 116 ***                 15.0      999.0        1.1         .1
  -2.30200   0.00000   0.00000     .55000    -.00250    -.56500    0.00000    0.00000
   0.00000   0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
61    EQUATION 119,*** MODEL 115 ***                 15.0      999.0        1.1         .1
  -2.70700   0.00000   0.00000     .55000    -.00250    -.54200    0.00000    0.00000
   0.00000   0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
62    EQUATION 136,*** MODEL 132 ***                 15.0      999.0        1.1         .1
  -1.67700   0.00000   0.00000     .74000    -.00050    -.53600    0.00000    0.00000
   0.00000   0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
63    EQUATION 135,*** MODEL 131 ***                 15.0      999.0        1.1         .1
   -.77690   0.00000   0.00000     .71000    -.00060    -.63700    0.00000    0.00000
   0.00000   0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
64    EQUATION 134,*** MODEL 130 ***                 15.0      999.0        1.1         .1
    .51683   0.00000   0.00000     .57000    -.00070    -.71900    0.00000    0.00000
   0.00000   0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
65    EQUATION 133,*** MODEL 129 ***                 15.0      999.0        1.1         .1
    .56020   0.00000   0.00000     .57000    -.00070    -.76200    0.00000    0.00000
   0.00000   0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
66    EQUATION 132,*** MODEL 128 ***                 15.0      999.0        1.1         .1
    .43170   0.00000   0.00000     .52000    -.00070    -.74000    0.00000    0.00000
   0.00000   0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
67    EQUATION 131,*** MODEL 127 ***                 15.0      999.0        1.1         .1
   -.85000   0.00000   0.00000     .56000    -.00070    -.77500    0.00000    0.00000
   0.00000   0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
68    EQUATION 130,*** MODEL 126 ***                 15.0      999.0        1.1         .1
  -1.25000   0.00000   0.00000     .57000    -.00070    -.76800    0.00000    0.00000
   0.00000   0.00000   0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
69    EQUATION 129,*** MODEL 125 ***                 15.0      999.0        1.1         .1
  -2.06000   0.00000   0.00000     .58000    -.00070    -.76100    0.00000    0.00000
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 0.00000   0.00000   0.00000   0.00000    0.00000   0.00000    0.00000    0.00000
70  EQUATION 128,*** MODEL 124 ***         15.0      999.0        1.1         .1
-2.38000   0.00000   0.00000    .59000    -.00070   -.76000    0.00000    0.00000
 0.00000   0.00000   0.00000   0.00000    0.00000   0.00000    0.00000    0.00000
71  NRC 1, FQ 1,   .5 HZ, CURVE  7           0.0        4.4        3.1         .1
 2.20656    .57600   -.00281   -.41700    1.30100  -4.37100    0.00000    0.00000
 -.34344   1.15000   -.00281   -.41700    2.10000  -7.96800    0.00000    0.00000
72  NRC 1, FQ 2,  1.0 HZ, CURVE  7           0.0        4.4        3.1         .1
 2.10784    .57600   -.00281   -.41700    1.30100  -4.37100    0.00000    0.00000
 -.44216   1.15000   -.00281   -.41700    2.10000  -7.96800    0.00000    0.00000
73  NRC 1, FQ 3,  2.5 HZ, CURVE  7           0.0        4.4        3.1         .1
 1.97740    .57600   -.00281   -.41700    1.30100  -4.37100    0.00000    0.00000
 -.57260   1.15000   -.00281   -.41700    2.10000  -7.96800    0.00000    0.00000
74  NRC 1, FQ 4,  3.3 HZ, CURVE  7           0.0        4.4        3.1         .1
 1.66913    .57600   -.00281   -.41700    1.30100  -4.37100    0.00000    0.00000
 -.88087   1.15000   -.00281   -.41700    2.10000  -7.96800    0.00000    0.00000
75  NRC 1, FQ 5,  5.0 HZ, CURVE  7           0.0        4.4        3.1         .1
 1.20815    .57600   -.00281   -.41700    1.30100  -4.37100    0.00000    0.00000
-1.34185   1.15000   -.00281   -.41700    2.10000  -7.96800    0.00000    0.00000
76  NRC 1, FQ 6, 10.0 HZ, CURVE  7           0.0        4.4        3.1         .1
  .39139    .57600   -.00281   -.41700    1.30100  -4.37100    0.00000    0.00000
-2.15861   1.15000   -.00281   -.41700    2.10000  -7.96800    0.00000    0.00000
77  NRC 1, FQ 7, 12.5 HZ, CURVE  7           0.0        4.4        3.1         .1
  .06872    .57600   -.00281   -.41700    1.30100  -4.37100    0.00000    0.00000
-2.48128   1.15000   -.00281   -.41700    2.10000  -7.96800    0.00000    0.00000
78  NRC 1, FQ 8, 20.0 HZ, CURVE  7           0.0        4.4        3.1         .1
 -.67358    .57600   -.00281   -.41700    1.30100  -4.37100    0.00000    0.00000
-3.22358   1.15000   -.00281   -.41700    2.10000  -7.96800    0.00000    0.00000
79  NRC 1, FQ 9, 25.0 HZ, CURVE  7           0.0        4.4        3.1         .1
-1.01833    .57600   -.00281   -.41700    1.30100  -4.37100    0.00000    0.00000
-3.56833   1.15000   -.00281   -.41700    2.10000  -7.96800    0.00000    0.00000
80  NRC 1, FQ 1,   .5 HZ, CURVE 25           0.0        5.6        4.1         .1
 1.15556    .79250   -.00200   -.79700     .01200    .91600     .26940    0.00000
-1.53984   1.27430   -.00200   -.79700     .01200   1.47300   -2.83800    0.00000
81  NRC 1, FQ 2,  1.0 HZ, CURVE 25           0.0        5.6        4.1         .1
 1.05684    .79250   -.00200   -.79700     .01200    .91600     .26940    0.00000
-1.63856   1.27430   -.00200   -.79700     .01200   1.47300   -2.83800    0.00000
82  NRC 1, FQ 3,  2.5 HZ, CURVE 25           0.0        5.6        4.1         .1
  .92640    .79250   -.00200   -.79700     .01200    .91600     .26940    0.00000
-1.76900   1.27430   -.00200   -.79700     .01200   1.47300   -2.83800    0.00000
83  NRC 1, FQ 4,  3.3 HZ, CURVE 25           0.0        5.6        4.1         .1
  .61813    .79250   -.00200   -.79700     .01200    .91600     .26940    0.00000
-2.07727   1.27430   -.00200   -.79700     .01200   1.47300   -2.83800    0.00000
84  NRC 1, FQ 5,  5.0 HZ, CURVE 25           0.0        5.6        4.1         .1
  .15715    .79250   -.00200   -.79700     .01200    .91600     .26940    0.00000
-2.53825   1.27430   -.00200   -.79700     .01200   1.47300   -2.83800    0.00000
85  NRC 1, FQ 6, 10.0 HZ, CURVE 25           0.0        5.6        4.1         .1
 -.65961    .79250   -.00200   -.79700     .01200    .91600     .26940    0.00000
-3.35501   1.27430   -.00200   -.79700     .01200   1.47300   -2.83800    0.00000
86  NRC 1, FQ 7, 12.5 HZ, CURVE 25           0.0        5.6        4.1         .1
 -.98228    .79250   -.00200   -.79700     .01200    .91600     .26940    0.00000
-3.67768   1.27430   -.00200   -.79700     .01200   1.47300   -2.83800    0.00000
87  NRC 1, FQ 8, 20.0 HZ, CURVE 25           0.0        5.6        4.1         .1
-1.72458    .79250   -.00200   -.79700     .01200    .91600     .26940    0.00000
-4.41998   1.27430   -.00200   -.79700     .01200   1.47300   -2.83800    0.00000
88  NRC 1, FQ 9, 25.0 HZ, CURVE 25           0.0        5.6        4.1         .1
-2.06933    .79250   -.00200   -.79700     .01200    .91600     .26940    0.00000
-4.76473   1.27430   -.00200   -.79700     .01200   1.47300   -2.83800    0.00000
89  ATC 1, FQ 1,   .5 HZ, CURVE  7           0.0        4.4        3.1         .1
 1.97955    .57600   -.00281   -.41700    1.30100  -4.37100    0.00000    0.00000
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  -.57045   1.15000   -.00281   -.41700   2.10000  -7.96800   0.00000   0.00000
90  ATC 1, FQ 2,  1.0 HZ, CURVE   7           0.0       4.4       3.1        .1
  2.09134    .57600   -.00281   -.41700   1.30100  -4.37100   0.00000   0.00000
  -.45866   1.15000   -.00281   -.41700   2.10000  -7.96800   0.00000   0.00000
91  ATC 1, FQ 3,  2.5 HZ, CURVE   7           0.0       4.4       3.1        .1
  2.05212    .57600   -.00281   -.41700   1.30100  -4.37100   0.00000   0.00000
  -.49788   1.15000   -.00281   -.41700   2.10000  -7.96800   0.00000   0.00000
92  ATC 1, FQ 4,  3.3 HZ, CURVE   7           0.0       4.4       3.1        .1
  1.77449    .57600   -.00281   -.41700   1.30100  -4.37100   0.00000   0.00000
  -.77551   1.15000   -.00281   -.41700   2.10000  -7.96800   0.00000   0.00000
93  ATC 1, FQ 5,  5.0 HZ, CURVE   7           0.0       4.4       3.1        .1
  1.35898    .57600   -.00281   -.41700   1.30100  -4.37100   0.00000   0.00000
 -1.19102   1.15000   -.00281   -.41700   2.10000  -7.96800   0.00000   0.00000
94  ATC 1, FQ 6, 10.0 HZ, CURVE   7           0.0       4.4       3.1        .1
   .43263    .57600   -.00281   -.41700   1.30100  -4.37100   0.00000   0.00000
 -2.11737   1.15000   -.00281   -.41700   2.10000  -7.96800   0.00000   0.00000
95  ATC 1, FQ 7, 12.5 HZ, CURVE   7           0.0       4.4       3.1        .1
   .10861    .57600   -.00281   -.41700   1.30100  -4.37100   0.00000   0.00000
 -2.44139   1.15000   -.00281   -.41700   2.10000  -7.96800   0.00000   0.00000
96  ATC 1, FQ 8, 20.0 HZ, CURVE   7           0.0       4.4       3.1        .1
  -.54483    .57600   -.00281   -.41700   1.30100  -4.37100   0.00000   0.00000
 -3.09483   1.15000   -.00281   -.41700   2.10000  -7.96800   0.00000   0.00000
97  ATC 1, FQ 9, 25.0 HZ, CURVE   7           0.0       4.4       3.1        .1
  -.83745    .57600   -.00281   -.41700   1.30100  -4.37100   0.00000   0.00000
 -3.38745   1.15000   -.00281   -.41700   2.10000  -7.96800   0.00000   0.00000
98  ATC 1, FQ 1,   .5 HZ, CURVE  25           0.0       5.6       4.1        .1
   .92855    .79250   -.00200   -.79700    .01200    .91600    .26940   0.00000
 -1.76685   1.27430   -.00200   -.79700    .01200   1.47300  -2.83800   0.00000
99  ATC 1, FQ 2,  1.0 HZ, CURVE  25           0.0       5.6       4.1        .1
  1.04034    .79250   -.00200   -.79700    .01200    .91600    .26940   0.00000
 -1.65506   1.27430   -.00200   -.79700    .01200   1.47300  -2.83800   0.00000
100  ATC 1, FQ 3,  2.5 HZ, CURVE 25           0.0       5.6       4.1        .1
  1.00112    .79250   -.00200   -.79700    .01200    .91600    .26940   0.00000
 -1.69428   1.27430   -.00200   -.79700    .01200   1.47300  -2.83800   0.00000
101  ATC 1, FQ 4,  3.3 HZ, CURVE 25           0.0       5.6       4.1        .1
   .72349    .79250   -.00200   -.79700    .01200    .91600    .26940   0.00000
 -1.97191   1.27430   -.00200   -.79700    .01200   1.47300  -2.83800   0.00000
102  ATC 1, FQ 5,  5.0 HZ, CURVE 25           0.0       5.6       4.1        .1
   .30798    .79250   -.00200   -.79700    .01200    .91600    .26940   0.00000
 -2.38742   1.27430   -.00200   -.79700    .01200   1.47300  -2.83800   0.00000
103  ATC 1, FQ 6, 10.0 HZ, CURVE 25           0.0       5.6       4.1        .1
  -.61837    .79250   -.00200   -.79700    .01200    .91600    .26940   0.00000
 -3.31377   1.27430   -.00200   -.79700    .01200   1.47300  -2.83800   0.00000
104  ATC 1, FQ 7, 12.5 HZ, CURVE 25           0.0       5.6       4.1        .1
  -.94239    .79250   -.00200   -.79700    .01200    .91600    .26940   0.00000
 -3.63779   1.27430   -.00200   -.79700    .01200   1.47300  -2.83800   0.00000
105  ATC 1, FQ 8, 20.0 HZ, CURVE 25           0.0       5.6       4.1        .1
 -1.59583    .79250   -.00200   -.79700    .01200    .91600    .26940   0.00000
 -4.29123   1.27430   -.00200   -.79700    .01200   1.47300  -2.83800   0.00000
106  ATC 1, FQ 9, 25.0 HZ, CURVE 25           0.0       5.6       4.1        .1
 -1.88845    .79250   -.00200   -.79700    .01200    .91600    .26940   0.00000
 -4.58385   1.27430   -.00200   -.79700    .01200   1.47300  -2.83800   0.00000
107     NWK FREQ 1 ,ANCHORS   7  37           0.0    2000.0       3.1       3.1
 -7.78922   2.30000   -.00122   -.42000   2.10000  -7.97000   1.00000   0.00000
   .94669   1.15000   -.00281   -.41700   2.10000  -7.96800   0.00000   0.00000
108     NWK FREQ 2 ,ANCHORS   7  37           0.0    2000.0       3.1       3.1
 -7.78922   2.30000   -.00122   -.42000   2.10000  -7.97000   1.00000   0.00000
   .25354   1.15000   -.00281   -.41700   2.10000  -7.96800   0.00000   0.00000
109     NWK FREQ 3 ,ANCHORS   7  37           0.0    2000.0       3.1       3.1
 -7.78922   2.30000   -.00122   -.42000   2.10000  -7.97000   1.00000   0.00000
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 -.66275   1.15000   -.00281   -.41700    2.10000   -7.96800   0.00000   0.00000
110    NWK FREQ 4 ,ANCHORS   7  37               0.0     2000.0       3.1       3.1
 -7.78922   2.30000   -.00122   -.42000    2.10000   -7.97000   1.00000   0.00000
  -.94038   1.15000   -.00281   -.41700    2.10000   -7.96800   0.00000   0.00000
111    NWK FREQ 5 ,ANCHORS   7  37               0.0     2000.0       3.1       3.1
 -7.78922   2.30000   -.00122   -.42000    2.10000   -7.97000   1.00000   0.00000
 -1.35590   1.15000   -.00281   -.41700    2.10000   -7.96800   0.00000   0.00000
112    NWK FREQ 6 ,ANCHORS   7  37               0.0     2000.0       3.1       3.1
 -7.78922   2.30000   -.00122   -.42000    2.10000   -7.97000   1.00000   0.00000
 -2.16737   1.15000   -.00281   -.41700    2.10000   -7.96800   0.00000   0.00000
113    NWK FREQ 7 ,ANCHORS   7  37               0.0     2000.0       3.1       3.1
 -7.78922   2.30000   -.00122   -.42000    2.10000   -7.97000   1.00000   0.00000
 -2.50884   1.15000   -.00281   -.41700    2.10000   -7.96800   0.00000   0.00000
114    NWK FREQ 8 ,ANCHORS   7  37               0.0     2000.0       3.1       3.1
 -7.78922   2.30000   -.00122   -.42000    2.10000   -7.97000   1.00000   0.00000
 -3.22807   1.15000   -.00281   -.41700    2.10000   -7.96800   0.00000   0.00000
115    NWK FREQ 9 ,ANCHORS   7  37               0.0     2000.0       3.1       3.1
 -7.78922   2.30000   -.00122   -.42000    2.10000   -7.97000   1.00000   0.00000
 -3.56954   1.15000   -.00281   -.41700    2.10000   -7.96800   0.00000   0.00000
116    NWK FREQ 1 ,ANCHORS  25  37               0.0     2000.0       4.1       3.1
 -7.78922   2.30000   -.00122   -.42000    2.10000   -7.97000   1.00000   0.00000
  -.24701   1.27430   -.00200   -.79700     .01200    1.47300  -2.83800   0.00000
117    NWK FREQ 2 ,ANCHORS  25  37               0.0     2000.0       4.1       3.1
 -7.78922   2.30000   -.00122   -.42000    2.10000   -7.97000   1.00000   0.00000
  -.94016   1.27430   -.00200   -.79700     .01200    1.47300  -2.83800   0.00000
118    NWK FREQ 3 ,ANCHORS  25  37               0.0     2000.0       4.1       3.1
 -7.78922   2.30000   -.00122   -.42000    2.10000   -7.97000   1.00000   0.00000
 -1.85645   1.27430   -.00200   -.79700     .01200    1.47300  -2.83800   0.00000
119    NWK FREQ 4 ,ANCHORS  25  37               0.0     2000.0       4.1       3.1
 -7.78922   2.30000   -.00122   -.42000    2.10000   -7.97000   1.00000   0.00000
 -2.13408   1.27430   -.00200   -.79700     .01200    1.47300  -2.83800   0.00000
120    NWK FREQ 5 ,ANCHORS  25  37               0.0     2000.0       4.1       3.1
 -7.78922   2.30000   -.00122   -.42000    2.10000   -7.97000   1.00000   0.00000
 -2.54960   1.27430   -.00200   -.79700     .01200    1.47300  -2.83800   0.00000
121    NWK FREQ 6 ,ANCHORS  25  37               0.0     2000.0       4.1       3.1
 -7.78922   2.30000   -.00122   -.42000    2.10000   -7.97000   1.00000   0.00000
 -3.36107   1.27430   -.00200   -.79700     .01200    1.47300  -2.83800   0.00000
122    NWK FREQ 7 ,ANCHORS  25  37               0.0     2000.0       4.1       3.1
 -7.78922   2.30000   -.00122   -.42000    2.10000   -7.97000   1.00000   0.00000
 -3.70254   1.27430   -.00200   -.79700     .01200    1.47300  -2.83800   0.00000
123    NWK FREQ 8 ,ANCHORS  25  37               0.0     2000.0       4.1       3.1
 -7.78922   2.30000   -.00122   -.42000    2.10000   -7.97000   1.00000   0.00000
 -4.42177   1.27430   -.00200   -.79700     .01200    1.47300  -2.83800   0.00000
124    NWK FREQ 9 ,ANCHORS  25  37               0.0     2000.0       4.1       3.1
 -7.78922   2.30000   -.00122   -.42000    2.10000   -7.97000   1.00000   0.00000
 -4.76324   1.27430   -.00200   -.79700     .01200    1.47300  -2.83800   0.00000
125   *** TRIFUNAC FREQ 1                       20.0      999.0       1.1        .1
   .09200   0.00000   0.00000    .80600    -.00089    -.94300   0.00000   -.16480
  0.00000   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
126   *** TRIFUNAC FREQ 2                       20.0      999.0       1.1        .1
   .27300   0.00000   0.00000    .75300    -.00083    -.88100   0.00000    .05760
  0.00000   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
127   *** TRIFUNAC FREQ 3                       20.0      999.0       1.1        .1
   .25000   0.00000   0.00000    .66800    -.00073    -.78100   0.00000    .34200
  0.00000   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
128   *** TRIFUNAC FREQ 4                       20.0      999.0       1.1        .1
   .09600   0.00000   0.00000    .65400    -.00072    -.76500   0.00000    .47200
  0.00000   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
129   *** TRIFUNAC FREQ 5                       20.0      999.0       1.1        .1
  -.36300   0.00000   0.00000    .65600    -.00072    -.76800   0.00000    .68000
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  0.00000   0.00000  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
130  *** TRIFUNAC FREQ 6                      20.0     999.0       1.1        .1
 -1.45400   0.00000  0.00000    .67700   -.00074   -.79200   0.00000    .87200
  0.00000   0.00000  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
131  *** TRIFUNAC FREQ 7                      20.0     999.0       1.1        .1
 -1.81900   0.00000  0.00000    .68600   -.00075   -.80300   0.00000    .87600
  0.00000   0.00000  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
132  *** TRIFUNAC FREQ 8                      20.0     999.0       1.1        .1
 -2.48300   0.00000  0.00000    .70000   -.00077   -.81900   0.00000    .85600
  0.00000   0.00000  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
133  *** TRIFUNAC FREQ 9                      20.0     999.0       1.1        .1
 -2.75800   0.00000  0.00000    .70700   -.00078   -.82700   0.00000    .83400
  0.00000   0.00000  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
134  ATC 2, FQ 1,    .5 HZ, CURVE  28          0.0     999.0       2.1        .1
  1.24955   1.24000  0.00000   0.00000  -1.24000  25.00000   0.00000   0.00000
 -1.91045   0.00000  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
135  ATC 2, FQ 2,   1.0 HZ, CURVE  28          0.0     999.0       2.1        .1
  1.36134   1.24000  0.00000   0.00000  -1.24000  25.00000   0.00000   0.00000
 -1.79866   0.00000  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
136  ATC 2, FQ 3,   2.5 HZ, CURVE  28          0.0     999.0       2.1        .1
  1.32212   1.24000  0.00000   0.00000  -1.24000  25.00000   0.00000   0.00000
 -1.83788   0.00000  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
137  ATC 2, FQ 4,   3.3 HZ, CURVE  28          0.0     999.0       2.1        .1
  1.04449   1.24000  0.00000   0.00000  -1.24000  25.00000   0.00000   0.00000
 -2.11551   0.00000  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
138  ATC 2, FQ 5,   5.0 HZ, CURVE  28          0.0     999.0       2.1        .1
   .62898   1.24000  0.00000   0.00000  -1.24000  25.00000   0.00000   0.00000
 -2.53102   0.00000  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
139  ATC 2, FQ 6,  10.0 HZ, CURVE  28          0.0     999.0       2.1        .1
  -.29737   1.24000  0.00000   0.00000  -1.24000  25.00000   0.00000   0.00000
 -3.45737   0.00000  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
140  ATC 2, FQ 7,  12.5 HZ, CURVE  28          0.0     999.0       2.1        .1
  -.62139   1.24000  0.00000   0.00000  -1.24000  25.00000   0.00000   0.00000
 -3.78139   0.00000  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
141  ATC 2, FQ 8,  20.0 HZ, CURVE  28          0.0     999.0       2.1        .1
 -1.27483   1.24000  0.00000   0.00000  -1.24000  25.00000   0.00000   0.00000
 -4.43483   0.00000  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
142  ATC 2, FQ 9,  25.0 HZ, CURVE  28          0.0     999.0       2.1        .1
 -1.56745   1.24000  0.00000   0.00000  -1.24000  25.00000   0.00000   0.00000
 -4.72745   0.00000  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
143  ATC 2, FQ 1,    .5 HZ, CURVE  24         15.0     999.0       5.1        .1
  -.44045   0.00000  1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
 -1.91045   0.00000  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
144  ATC 2, FQ 2,   1.0 HZ, CURVE  24         15.0     999.0       5.1        .1
  -.32866   0.00000  1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
 -1.79866   0.00000  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
145  ATC 2, FQ 3,   2.5 HZ, CURVE  24         15.0     999.0       5.1        .1
  -.36788   0.00000  1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
 -1.83788   0.00000  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
146  ATC 2, FQ 4,   3.3 HZ, CURVE  24         15.0     999.0       5.1        .1
  -.64551   0.00000  1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
 -2.11551   0.00000  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
147  ATC 2, FQ 5,   5.0 HZ, CURVE  24         15.0     999.0       5.1        .1
 -1.06102   0.00000  1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
 -2.53102   0.00000  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
148  ATC 2, FQ 6,  10.0 HZ, CURVE  24         15.0     999.0       5.1        .1
 -1.98737   0.00000  1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
 -3.45737   0.00000  0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
149  ATC 2, FQ 7,  12.5 HZ, CURVE  24         15.0     999.0       5.1        .1
 -2.31139   0.00000  1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
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  -3.78139   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
150  ATC 2, FQ 8, 20.0 HZ, CURVE  24           15.0      999.0       5.1        .1
  -2.96483   0.00000   1.20000  -1.02000    0.00000    0.00000   0.00000   0.00000
  -4.43483   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
151  ATC 2, FQ 9, 25.0 HZ, CURVE  24           15.0      999.0       5.1        .1
  -3.25745   0.00000   1.20000  -1.02000    0.00000    0.00000   0.00000   0.00000
  -4.72745   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
152  ATC 2, FQ 1,   .5 HZ, CURVE   5            0.0      999.0       2.1        .1
   -.44045   1.10000   0.00000   -.00170    -.88000    0.00000   0.00000   0.00000
  -1.91045   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
153  ATC 2, FQ 2,  1.0 HZ, CURVE   5            0.0      999.0       2.1        .1
   -.32866   1.10000   0.00000   -.00170    -.88000    0.00000   0.00000   0.00000
  -1.79866   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
154  ATC 2, FQ 3,  2.5 HZ, CURVE   5            0.0      999.0       2.1        .1
   -.36788   1.10000   0.00000   -.00170    -.88000    0.00000   0.00000   0.00000
  -1.83788   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
155  ATC 2, FQ 4,  3.3 HZ, CURVE   5            0.0      999.0       2.1        .1
   -.64551   1.10000   0.00000   -.00170    -.88000    0.00000   0.00000   0.00000
  -2.11551   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
156  ATC 2, FQ 5,  5.0 HZ, CURVE   5            0.0      999.0       2.1        .1
  -1.06102   1.10000   0.00000   -.00170    -.88000    0.00000   0.00000   0.00000
  -2.53102   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
157  ATC 2, FQ 6, 10.0 HZ, CURVE   5            0.0      999.0       2.1        .1
  -1.98737   1.10000   0.00000   -.00170    -.88000    0.00000   0.00000   0.00000
  -3.45737   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
158  ATC 2, FQ 7, 12.5 HZ, CURVE   5            0.0      999.0       2.1        .1
  -2.31139   1.10000   0.00000   -.00170    -.88000    0.00000   0.00000   0.00000
  -3.78139   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
159  ATC 2, FQ 8, 20.0 HZ, CURVE   5            0.0      999.0       2.1        .1
  -2.96483   1.10000   0.00000   -.00170    -.88000    0.00000   0.00000   0.00000
  -4.43483   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
160  ATC 2, FQ 9, 25.0 HZ, CURVE   5            0.0      999.0       2.1        .1
  -3.25745   1.10000   0.00000   -.00170    -.88000    0.00000   0.00000   0.00000
  -4.72745   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
161  NRC 2, FQ 1,   .5 HZ, CURVE  28            0.0      999.0       2.1        .1
   1.47656   1.24000   0.00000   0.00000   -1.24000   25.00000   0.00000   0.00000
  -1.68344   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
162  NRC 2, FQ 2,  1.0 HZ, CURVE  28            0.0      999.0       2.1        .1
   1.37784   1.24000   0.00000   0.00000   -1.24000   25.00000   0.00000   0.00000
  -1.78216   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
163  NRC 2, FQ 3,  2.5 HZ, CURVE  28            0.0      999.0       2.1        .1
   1.24740   1.24000   0.00000   0.00000   -1.24000   25.00000   0.00000   0.00000
  -1.91260   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
164  NRC 2, FQ 4,  3.3 HZ, CURVE  28            0.0      999.0       2.1        .1
    .93913   1.24000   0.00000   0.00000   -1.24000   25.00000   0.00000   0.00000
  -2.22087   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
165  NRC 2, FQ 5,  5.0 HZ, CURVE  28            0.0      999.0       2.1        .1
    .47815   1.24000   0.00000   0.00000   -1.24000   25.00000   0.00000   0.00000
  -2.68185   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
166  NRC 2, FQ 6, 10.0 HZ, CURVE  28            0.0      999.0       2.1        .1
   -.33861   1.24000   0.00000   0.00000   -1.24000   25.00000   0.00000   0.00000
  -3.49861   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
167  NRC 2, FQ 7, 12.5 HZ, CURVE  28            0.0      999.0       2.1        .1
   -.66128   1.24000   0.00000   0.00000   -1.24000   25.00000   0.00000   0.00000
  -3.82128   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
168  NRC 2, FQ 8, 20.0 HZ, CURVE  28            0.0      999.0       2.1        .1
  -1.40358   1.24000   0.00000   0.00000   -1.24000   25.00000   0.00000   0.00000
  -4.56358   0.00000   0.00000   0.00000    0.00000    0.00000   0.00000   0.00000
169  NRC 2, FQ 9, 25.0 HZ, CURVE  28            0.0      999.0       2.1        .1
  -1.74833   1.24000   0.00000   0.00000   -1.24000   25.00000   0.00000   0.00000
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   -4.90833   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
170  NRC 2, FQ 1,    .5 HZ, CURVE  24          15.0     999.0       5.1        .1
    -.21344   0.00000   1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
   -1.68344   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
171  NRC 2, FQ 2,   1.0 HZ, CURVE  24          15.0     999.0       5.1        .1
    -.31216   0.00000   1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
   -1.78216   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
172  NRC 2, FQ 3,   2.5 HZ, CURVE  24          15.0     999.0       5.1        .1
    -.44260   0.00000   1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
   -1.91260   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
173  NRC 2, FQ 4,   3.3 HZ, CURVE  24          15.0     999.0       5.1        .1
    -.75087   0.00000   1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
   -2.22087   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
174  NRC 2, FQ 5,   5.0 HZ, CURVE  24          15.0     999.0       5.1        .1
   -1.21185   0.00000   1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
   -2.68185   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
175  NRC 2, FQ 6,  10.0 HZ, CURVE  24          15.0     999.0       5.1        .1
   -2.02861   0.00000   1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
   -3.49861   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
176  NRC 2, FQ 7,  12.5 HZ, CURVE  24          15.0     999.0       5.1        .1
   -2.35128   0.00000   1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
   -3.82128   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
177  NRC 2, FQ 8,  20.0 HZ, CURVE  24          15.0     999.0       5.1        .1
   -3.09358   0.00000   1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
   -4.56358   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
178  NRC 2, FQ 9,  25.0 HZ, CURVE  24          15.0     999.0       5.1        .1
   -3.43833   0.00000   1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
   -4.90833   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
179  NRC 2, FQ 1,    .5 HZ, CURVE   5           0.0     999.0       2.1        .1
    -.21344   1.10000   0.00000   -.00170   -.88000   0.00000   0.00000   0.00000
   -1.68344   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
180  NRC 2, FQ 2,   1.0 HZ, CURVE   5           0.0     999.0       2.1        .1
    -.31216   1.10000   0.00000   -.00170   -.88000   0.00000   0.00000   0.00000
   -1.78216   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
181  NRC 2, FQ 3,   2.5 HZ, CURVE   5           0.0     999.0       2.1        .1
    -.44260   1.10000   0.00000   -.00170   -.88000   0.00000   0.00000   0.00000
   -1.91260   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
182  NRC 2, FQ 4,   3.3 HZ, CURVE   5           0.0     999.0       2.1        .1
    -.75087   1.10000   0.00000   -.00170   -.88000   0.00000   0.00000   0.00000
   -2.22087   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
183  NRC 2, FQ 5,   5.0 HZ, CURVE   5           0.0     999.0       2.1        .1
   -1.21185   1.10000   0.00000   -.00170   -.88000   0.00000   0.00000   0.00000
   -2.68185   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
184  NRC 2, FQ 6,  10.0 HZ, CURVE   5           0.0     999.0       2.1        .1
   -2.02861   1.10000   0.00000   -.00170   -.88000   0.00000   0.00000   0.00000
   -3.49861   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
185  NRC 2, FQ 7,  12.5 HZ, CURVE   5           0.0     999.0       2.1        .1
   -2.35128   1.10000   0.00000   -.00170   -.88000   0.00000   0.00000   0.00000
   -3.82128   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
186  NRC 2, FQ 8,  20.0 HZ, CURVE   5           0.0     999.0       2.1        .1
   -3.09358   1.10000   0.00000   -.00170   -.88000   0.00000   0.00000   0.00000
   -4.56358   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
187  NRC 2, FQ 9,  25.0 HZ, CURVE   5           0.0     999.0       2.1        .1
   -3.43833   1.10000   0.00000   -.00170   -.88000   0.00000   0.00000   0.00000
   -4.90833   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
188     NWK  FREQ 1 ,ANCHORS  28  50           15.0    2000.0       2.1       1.1
   -6.21922   2.30000   0.00000   0.00000   0.00000  -1.00000   0.00000   0.00000
    2.76669   1.24000   0.00000   0.00000  -1.24000  25.00000   0.00000   0.00000
189     NWK  FREQ 2 ,ANCHORS  28  50           15.0    2000.0       2.1       1.1
   -6.21922   2.30000   0.00000   0.00000   0.00000  -1.00000   0.00000   0.00000
```

```
  2.07354   1.24000   0.00000   0.00000  -1.24000  25.00000   0.00000   0.00000
190   NWK FREQ 3 ,ANCHORS  28  50          15.0    2000.0       2.1       1.1
 -6.21922   2.30000   0.00000   0.00000   0.00000  -1.00000   0.00000   0.00000
  1.15725   1.24000   0.00000   0.00000  -1.24000  25.00000   0.00000   0.00000
191   NWK FREQ 4 ,ANCHORS  28  50          15.0    2000.0       2.1       1.1
 -6.21922   2.30000   0.00000   0.00000   0.00000  -1.00000   0.00000   0.00000
   .87962   1.24000   0.00000   0.00000  -1.24000  25.00000   0.00000   0.00000
192   NWK FREQ 5 ,ANCHORS  28  50          15.0    2000.0       2.1       1.1
 -6.21922   2.30000   0.00000   0.00000   0.00000  -1.00000   0.00000   0.00000
   .46410   1.24000   0.00000   0.00000  -1.24000  25.00000   0.00000   0.00000
193   NWK FREQ 6 ,ANCHORS  28  50          15.0    2000.0       2.1       1.1
 -6.21922   2.30000   0.00000   0.00000   0.00000  -1.00000   0.00000   0.00000
  -.34737   1.24000   0.00000   0.00000  -1.24000  25.00000   0.00000   0.00000
194   NWK FREQ 7 ,ANCHORS  28  50          15.0    2000.0       2.1       1.1
 -6.21922   2.30000   0.00000   0.00000   0.00000  -1.00000   0.00000   0.00000
  -.68884   1.24000   0.00000   0.00000  -1.24000  25.00000   0.00000   0.00000
195   NWK FREQ 8 ,ANCHORS  28  50          15.0    2000.0       2.1       1.1
 -6.21922   2.30000   0.00000   0.00000   0.00000  -1.00000   0.00000   0.00000
 -1.40807   1.24000   0.00000   0.00000  -1.24000  25.00000   0.00000   0.00000
196   NWK FREQ 9 ,ANCHORS  28  50          15.0    2000.0       2.1       1.1
 -6.21922   2.30000   0.00000   0.00000   0.00000  -1.00000   0.00000   0.00000
 -1.74954   1.24000   0.00000   0.00000  -1.24000  25.00000   0.00000   0.00000
197   NWK FREQ 1 ,ANCHORS  24  36           0.0    2000.0       5.1       1.1
  -.42322    .95000   0.00000   0.00000   -.00230   -.76500   0.00000   0.00000
  1.07669   0.00000   1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
198   NWK FREQ 2 ,ANCHORS  24  36           0.0    2000.0       5.1       1.1
  -.42322    .95000   0.00000   0.00000   -.00230   -.76500   0.00000   0.00000
   .38354   0.00000   1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
199   NWK FREQ 3 ,ANCHORS  24  36           0.0    2000.0       5.1       1.1
  -.42322    .95000   0.00000   0.00000   -.00230   -.76500   0.00000   0.00000
  -.53275   0.00000   1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
200   NWK FREQ 4 ,ANCHORS  24  36           0.0    2000.0       5.1       1.1
  -.42322    .95000   0.00000   0.00000   -.00230   -.76500   0.00000   0.00000
  -.81038   0.00000   1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
201   NWK FREQ 5 ,ANCHORS  24  36           0.0    2000.0       5.1       1.1
  -.42322    .95000   0.00000   0.00000   -.00230   -.76500   0.00000   0.00000
 -1.22590   0.00000   1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
202   NWK FREQ 6 ,ANCHORS  24  36           0.0    2000.0       5.1       1.1
  -.42322    .95000   0.00000   0.00000   -.00230   -.76500   0.00000   0.00000
 -2.03737   0.00000   1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
203   NWK FREQ 7 ,ANCHORS  24  36           0.0    2000.0       5.1       1.1
  -.42322    .95000   0.00000   0.00000   -.00230   -.76500   0.00000   0.00000
 -2.37884   0.00000   1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
204   NWK FREQ 8 ,ANCHORS  24  36           0.0    2000.0       5.1       1.1
  -.42322    .95000   0.00000   0.00000   -.00230   -.76500   0.00000   0.00000
 -3.09807   0.00000   1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
205   NWK FREQ 9 ,ANCHORS  24  36           0.0    2000.0       5.1       1.1
  -.42322    .95000   0.00000   0.00000   -.00230   -.76500   0.00000   0.00000
 -3.43954   0.00000   1.20000  -1.02000   0.00000   0.00000   0.00000   0.00000
206   NWK FREQ 1 ,ANCHORS   5  52           0.0    2000.0       2.1       1.1
 -4.87922   1.70000   0.00000   0.00000   -.00100   -.75600   0.00000   0.00000
  1.07669   1.10000   0.00000   -.00170   -.88000   0.00000   0.00000   0.00000
207   NWK FREQ 2 ,ANCHORS   5  52           0.0    2000.0       2.1       1.1
 -4.87922   1.70000   0.00000   0.00000   -.00100   -.75600   0.00000   0.00000
   .38354   1.10000   0.00000   -.00170   -.88000   0.00000   0.00000   0.00000
208   NWK FREQ 3 ,ANCHORS   5  52           0.0    2000.0       2.1       1.1
 -4.87922   1.70000   0.00000   0.00000   -.00100   -.75600   0.00000   0.00000
  -.53275   1.10000   0.00000   -.00170   -.88000   0.00000   0.00000   0.00000
209   NWK FREQ 4 ,ANCHORS   5  52           0.0    2000.0       2.1       1.1
 -4.87922   1.70000   0.00000   0.00000   -.00100   -.75600   0.00000   0.00000
```

```
  -.81038   1.10000   0.00000   -.00170   -.88000   0.00000   0.00000   0.00000
210   NWK FREQ 5 ,ANCHORS    5  52            0.0    2000.0       2.1       1.1
 -4.87922   1.70000   0.00000   0.00000   -.00100   -.75600   0.00000   0.00000
 -1.22590   1.10000   0.00000   -.00170   -.88000   0.00000   0.00000   0.00000
211   NWK FREQ 6 ,ANCHORS    5  52            0.0    2000.0       2.1       1.1
 -4.87922   1.70000   0.00000   0.00000   -.00100   -.75600   0.00000   0.00000
 -2.03737   1.10000   0.00000   -.00170   -.88000   0.00000   0.00000   0.00000
212   NWK FREQ 7 ,ANCHORS    5  52            0.0    2000.0       2.1       1.1
 -4.87922   1.70000   0.00000   0.00000   -.00100   -.75600   0.00000   0.00000
 -2.37884   1.10000   0.00000   -.00170   -.88000   0.00000   0.00000   0.00000
213   NWK FREQ 8 ,ANCHORS    5  52            0.0    2000.0       2.1       1.1
 -4.87922   1.70000   0.00000   0.00000   -.00100   -.75600   0.00000   0.00000
 -3.09807   1.10000   0.00000   -.00170   -.88000   0.00000   0.00000   0.00000
214   NWK FREQ 9 ,ANCHORS    5  52            0.0    2000.0       2.1       1.1
 -4.87922   1.70000   0.00000   0.00000   -.00100   -.75600   0.00000   0.00000
 -3.43954   1.10000   0.00000   -.00170   -.88000   0.00000   0.00000   0.00000
```

TABLE A.2

FUNCTIONS FOR PREDICTION MODELS

```
   MODEL A  (MODEL INDEX = 1)
   *******
   LOG(ACC) = A1 + A2*MB + A3*ML + A4*IO + A5*R + A6*LOG(R) +
              A7*MB*R + A8
   FUNCTION AMODEL (XM,XI,R,ATTN,L)
   DIMENSION ATTN(1)
   AMODEL = ATTN(1+L) + XM*(ATTN(2+L)+ATTN(3+L)) + XI*ATTN(4+L) +
+       R*ATTN(5+L) + ATTN(6+L)*ALOG(R) + ATTN(7+L)*XM*R + ATTN(8+L)
   RETURN
   END

   MODEL B  (MODEL INDEX = 2)
   *******
   LOG(ACC) = B1 + B2*MB + B3*MBLG + B4*R + B5*LOG(B6+R) + B7*MB*R +
              B8*MB*MB*R
   FUNCTION BMODEL (XM,XI,R,ATTN,L)
   DIMENSION  ATTN(1)
   BMODEL = ATTN(1+L) + (ATTN(2+L)+ATTN(3+L))*XM + ATTN(4+L)*R +
+       ATTN(5+L)*ALOG(ATTN(6+L)+R) + R*XM*(ATTN(7+L)+ATTN(8+L)*XM)
   RETURN
   END

   MODEL C  (MODEL INDEX = 3)
   *******
   LOG(ACC) = C1 + C2*MB + C3*R + C4*LOG(R*(C7+R)+EXP(C5*MB+C6))
   FUNCTION CMODEL (XM,XI,R,ATTN,L)
   DIMENSION  ATTN(1)
   CMODEL = ATTN(1+L) + ATTN(2+L)*XM + ATTN(3+L)*R +
+       ATTN(4+L)*ALOG(R*(ATTN(7+L)+R)+EXP(ATTN(5+L)*XM+ATTN(6+L)))
   RETURN
   END

   MODEL D  (MODEL INDEX = 4)
   *******
   LOG(ACC) = D1 + D2*MB + D3*R + D4*LOG(R+D5*EXP(D6*MB+D7))
   FUNCTION DMODEL (XM,XI,R,ATTN,L)
   DIMENSION ATTN(1)
   DMODEL = ATTN(1+L) + ATTN(2+L)*XM + ATTN(3+L)*R +
+       ATTN(4+L)*ALOG(R+ATTN(5+L)*EXP(ATTN(6+L)*XM+ATTN(7+L)))
   RETURN
   END

   MODEL E  (MODEL INDEX = 5)
   *******
   LOG(ACC) = E1 + E3*MBLG + E4*LOG(R)
   FUNCTION EMODEL (XM,XI,R,ATTN,L)
   DIMENSION ATTN(1)
   EMODEL = ATTN(L+1) + ATTN(L+3)*XM + ATTN(L+4)*ALOG(R)
   RETURN
   END
```

SEISMIC HAZARD CHARACTERIZATION OF THE EASTERN
UNITED STATES

Feedback Questionnaire Q7
Zonation

FEEDBACK QUESTIONNAIRE Q7
Zonation

1. INTRODUCTION:

This questionnaire is part of the continuing project, initiated by the U.S. Nuclear Regulatory Commission (NRC), to develop a seismic hazard characterization -based in part on your expert opinions- for the region of the United States east of the Rocky Mountains. As part of the project we have developed a methodology including analytical work, computer development and data collection techniques. This methodology has been demonstrated in a set of applications to ten nuclear plant sites distributed over the entire Eastern United States (EUS). It has been validated by a series of sensitivity analyses, workshops and comparisons with other available techniques. We provided you copies of the reports documenting this effort. Bernreuter et al. (1985) and (1986). Our purpose is now to apply our methodology to all the nuclear plant sites in the EUS, as requested by the NRC.

The fields of science from which every seismic hazard analysis draws its input data have been in constant effervescence since the time that our data bases were generated. As our methodology relies entirely on the opinions of experts in these sciences, we have elected to reconvene our panels of experts to update our data bases prior to calculating the seismic hazard at all the sites. In this phase of the project, we primarily intend to revisit the data bases and do not contemplate making major changes in our methodology. However, we do not preclude small changes in the methodology which would be compatible with the schedule and the available level of effort. Thus, as an expert who contributed in the earlier phases of this project by providing your opinion regarding the zonation and seismicity of the EUS, we are asking you to review this document and answer the questions presented to you in Section 4.

The present phase of this project is the continuation of the Systematic Evaluation Program (SEP), and of the Seismic Hazard Characterization of the

Eastern United States Program (SHCP). These two programs were several years apart as to the dates of finalizing the methodologies and data bases. An important conclusion of the latter study (SHCP), 1985 was that the experts' opinion showed good stability in time.

In the last past few years there has been considerable research and applications in the fields involved in Seismic Hazard Analyses of the EUS. This activity was primarily initiated by the following events and possibly others:

- o Occurrence of the New Brunswick earthquakes,
- o Occurrence of the New Hampshire earthquakes,
- o Discovery of the Meers fault.
- o More recent occurrence of earthquakes in Northeast Ohio, near the Perry Nuclear Plant site.
- o Realization by the group of electric power utilities that an effort parallel to the NRC effort was desirable for assessing the hazard in the EUS.
- o Development of new theoretical means of assessing the strong ground motion at a site.

Thus, new seismicity data, new strong motion data, and new geological information are now available which were not available at the time of the beginning of SHCP. New solutions to the problems of incompleteness of the earthquake catalog and to the problem of existence of clusters in those catalogs have been proposed.

In addition, the effort of the electric power utilities directed by the Electric Power Research Institute (EPRI) has been very important in collecting and analyzing a large amount of data relevant to seismic hazard analyses. This includes geological data, and geophysical data such as gravity anomalies, heat flows, tectonic stresses, and geophysical profiling. The EPRI (1985) effort led to interesting, often new interpretations, of the seismicity of the EUS, which might be valuable to our experts to test their own opinions.

However, we want to re-emphasize that our study (SHCP) relies on the opinions of individual experts rather than any group or team opinion of the kind developed in the EPRI study. You, as an expert for the SHCP, are asked to review the latest scientific evidence relevant to seismic zonation and seismicity of the EUS and provide your input. You are free to modify your opinion or reiterate the interpretations of the data you derived in our earlier study. Thus, the purpose of this document is to make you aware of some of the possible areas that deserve your consideration in updating your opinion on the seismic zonation of the EUS.

Once again our elicitation process will be in two steps. First, your responses to this questionnaire (Q7) will be a set of seismic zonation maps, and tables of degrees of belief of existence and alternative shapes, exactly as in your responses to the first questionnaire (Q1) and feedback questionnaire (Q5), to which you responded in 1982-1984. In addition as we have modified slightly our way of eliciting your opinion about the seismicity parameters we will need to know your opinion regarding some of the parameters that we will use to present to you the seismicity data corresponding to your zonation maps. Secondly, in the seismicity questionnaire (Q8), you will be asked to reconsider your earthquake recurrence model for each zone you have defined.

In Section 2, we describe the elements of the zonation which will be updated in this questionnaire and we restate some of the definitions and our assumptions to avoid confusion with some of the definitions and assumptions used in other recent studies you may have been associated with. Section 3 describes the elements of the information that we will need to develop the feedback seismicity questionnaire (Q8).

Section 4.2 consists in the actual questions you will have to answer so that we can update your maps of seismic zonation. This section is essentially the same as the questions in questionnaires (Q1) and (Q5). Finally, Section 4.3 consists of questions you have to answer to help us to develop the next

questionnaire (Q8), specifically adapted to your zonation maps and your interpretation of incompleteness and clustering.

2. ELEMENTS TO BE UPDATED: ZONATION

2.1 Introduction

At this point and for the purpose of this questionnaire, on zonation, we limit ourselves to updating only your answers to the previous questionnaires on zonation (Q1 and Q5).

All the basic concepts and assumptions described in Q1 and Q5 are still valid. Thus, the seismicity of the EUS is still modeled by a set of seismic source zones along with by a model of earthquake occurrence for each zone.

Your answers to the questions in this questionnaire will be used to update your description of the seismic source zones. You will be asked to update your best estimate map. To express your uncertainty, you will be asked to update your map of alternative shapes and the tables of probability of existence and probability of shapes. In the following subsections, we review the elements of the update, re-state their definitions and note the conceptual and/or methodology differences with other studies you may be familiar with.

2.2 Source zone configuration: Best Estimate Map.

We assume that it is possible to identify zones where you believe that earthquakes of a common nature and frequency of occurrence may occur in the future. Once such a zone is identified, it is said to "exist". Thus a source zone is an area of the EUS which you believe needs to be identified as different from its surroundings. If you are not sure about the need for separate identification of a given zone, we say that you are not sure of its existence, and we ask you to express it as discussed below in Section 2.3 by giving your degree of belief in its existence.

Two important points of conceptual differences between our interpretation and that of the EPRI Study are the following:

- o The EPRI zones are associated with the presence of geological or geophysical "features", where the feature in interpreted loosely. Then that feature is considered to be active or inactive. It is considered to be active only if it can generate an earthquake of magnitude at least equal to M_0 (e.g. M_0= 5.0 for EPRI), otherwise it is considered to be inactive.

- o In our study a zone is associated with a distinct occurrence rate and distribution of earthquake magnitudes different from the surrounding region. The "existence" of a zone only depends on whether the seismicity is different from its surrounding region. If its seismicity is different, then the zone is considered to exist. The question of a zone being active (i.e. capable of producing an earthquake of magnitude at least M_0) or inactive does not become an element in formulating your degree of belief about the existence of a zone.

Can our methodology acommodate an aseismic area of the EUS? Certainly! If you consider an area to be aseismic and want to include it, just remember that an aseismic area has a seismicity different than the surrounding region. Thus, it should be identified as a zone, of course, with zero seismicity (input as part of the seismicity questionnaire). Suppose you are uncertain if it is aseismic. That can also be included, for example, as follows:

- o Suppose you believe it is aseismic but you believe there is a possibility that it has a non-zero activity level similar to surrounding region, then

  P (existence) = P (aseismic)

  P (not exist) = P (seismic and rate like host zone)

For this case the probability of existence refers to the probability of having a zone with zero seismicity.

- o Suppose if it is aseismic, it has activity level different from surrounding region, but its boundary shape is uncertain, then,

  P (exist) = 1.0 and the alternative shape with zero seismicity is given as an alternaitve,

Thus by using the probability of existence and alternative shape description, with the possibility of a zero seismicity, we can model any kind of combination.

In Section 4.2, you will be asked to reconsider your previous answers in defining a best estimate map. The best estimate map is still supposed to represent the seismic zonation map which in your opinion represents best the spatial distribution of future earthquakes in the EUS, i.e.. your degree of belief in the existence of each zone identified is $\geq$0.5.

2.3 Source zones: Probability of existence

As noted above, you may be uncertain about the need for identifying a particular area as a specific source zone , i.e.., all the scientific evidence you collected in favor of that particular alternative does not appear to convince you entirely. In that case you can express your uncertainty by giving your degree of belief in the need to identify that source zone (existence) by responding to the appropriate questions in Section 4.2.

As for the best estimate map itself, you may choose to keep the answer that you gave on the previous questionnaires (Q1 and Q5-feedback), however, you should feel free to update any answer which you believe does not correspond to your current thinking. The probability of existence of each source zone is an important element in the characterization of your uncertainty in the seismic

zonation, as we showed in the previous parts of this study that the uncertainty in the zonation is a significant contributor to the uncertainty in the hazard. Thus, in Section 4 you will be asked to carefully review your previous answers on your degrees of belief in the existence of each zone, which we have provided in Table A-1 and A-2. It was mentioned in Section 2.2 that the degree of belief in existence should not be confused with the probability of the source being active. In our methodology an existing source zone is always active, i.e., it is always capable of producing earthquakes of magnitude greater or equal to $M_0 = 3.75$.

For a zone represented on the best estimate map for which your degree of belief of its existence is less than one, we consider that it is possible to draw a map where that zone does not exist. In that case, you need to specify what this extracted area becomes in the new map. Figure 2.1 gives an example of such a case. In this example, the boundaries of B delimitate an area separate from zone A and zone C. In the alternative case when zone B does not exist, it becomes part of zone A (Map 2a) or part of zone C (map 2b). Zone A (or C) is called the host zone in our terminology.

You will be asked to review your previous responses as to which zones are considered as host zones for the zones with degree of belief of existence less than 1 and update them as you see fit.

2.4 Source zones: Alternative Shapes

Considering one source at a time or a cluster of zones at a time, you were asked in previous questionnaires to express your uncertainty in the shapes of the zones drawn on your best estimate map by providing alternate shapes and your degree of belief that the shape you suggest is the true shape.

Remembering that source zones are not necessarily associated with "features", we emphasize the fact that you are asked to provide alternative shapes rather than alternative scenarios as in the EPRI study. However, if you believe that

a given zone (or cluster of zones) could be the result of the existence of two different geological features, you may want to tailor the two alternative shapes to the associated features.

For example, zone A of Fig. 2.2a represents an area which is distinct from its surroundings when we review all the geological, geophysical, and seismological available data. We believe, from geophysical and geological information that there is a possibility that a fault exists at depth (e.g., a decollement fault identified as F on Fig. 2.2a). On the other hand, the historic seismicity, shown by dots on Fig. 2.2a tends to contradict the scenario of fault F. Thus, if we believe that the most likely source zone is zone A, closely associated with fault F, we may want to give an alternate shape A' for that same zone, where A' might follow more closely the trend in seismicity, as shown in Fig. 2.2b. As in the previous questionnaires, you will be asked to provide maps of alternative shapes and your degrees of belief (in Table A2) in the alternative shapes which you gave.

2.5 The Complementary Zone(s)

The concept of complementary zone (CZ) is an important one as the hazard at many sites in the EUS will depend directly on the characteristics of that zone. It is important to note that in our study every square kilometer of the EUS is part of a source zone. If it is not part of any of the zones identified in the best estimate map, it becomes, by default, part of the CZ since the CZ is defined as the complementary part to all zoned areas. Thus, the CZ provides for some default seismicity in the areas for which your lack of knowledge does not allow for some specific zonation. At the time of the last feedback, we refined the notion of CZ to that of regional CZ, in effect acknowledging that different large regions of the E.U.S. may have different tectonic (thus seismicity) regimes. Thus, you will be asked to review your answer concerning the CZ and, if you judge it necessary, to draw regional CZ's, that is, in effect, define regional CZ's as source zones.

Note that the definition of our CZ is conceptually different from the background zone used in the EPRI study. In the latter, it is assumed that there are features, in the unzoned area, which are either poorly known or of which the location is not known. It is then assumed that on the average a certain portion of this background zone contains active features, the rest of it being devoid of active features. The overall effect is obtained by averaging that portion over the entire background zone.

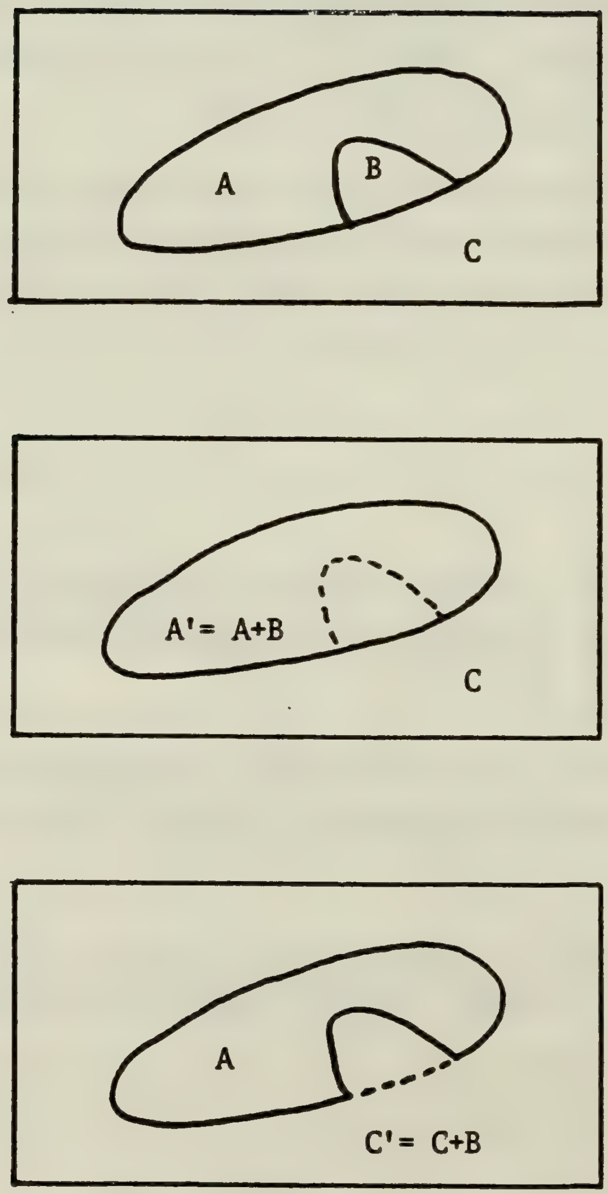
In our study we assume that our CZ is always active and basically it has the same definition as the other source zones. If you believe, however, that a given area of the EUS is aseismic, as before, you will be able to express this idea by choosing the proper seismicity parameters in the next questionnaire (Q8).

2.6 References for Section 2

Bernreuter, D.L., et al. (1985), Seismic Hazard Characterization of the Eastern United States: Vol 1: Methodology and Results for Ten Sites and Vol. 2: Questionnaries LLNL Report UCID 20421 Vol. 1 and 2.

Bernreuter, D.L., et al. (1986), A Limited Evaluation of the Difference Between the LLNL and EPRI Seismic Hazard Analysis Programs. LLNL Report UCID 20696.

EPRI (1985), Seismic Hazard Methodology for Nuclear Facilities in the Eastern United States: Vol. 1,2 and 3. Research Project Number P101-29 (Draft).



Map 1
Best Estimate Map (BEM)

Map 2a

Map 2b

Figure 2.1 The best estimate (map 1) is made of three source zones. Source zones A, B and C. The degree of belief on the existence of zone B is less than 1 (e.g., .8). Thus, we can draw another map (map 2) where zone B does not exist. (i.e., where zone B is not separated from its surroundings). In this case we can specify that B becomes part of A (map 2a) or part of C (map 2b).

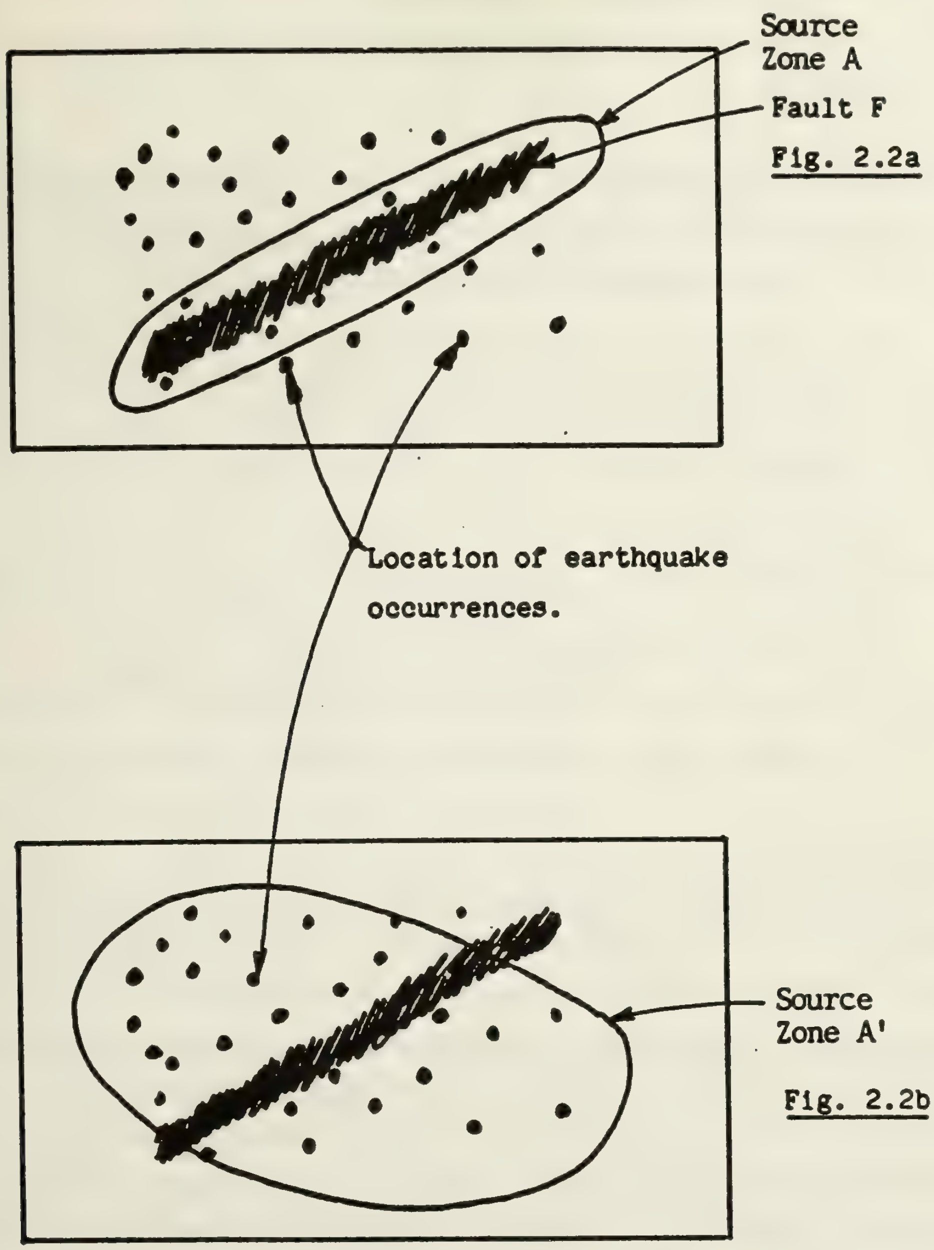


Fig. 2.2 Given that we need to identify zone A because it departs from its surroundings, two possible shapes are shown. One shape (zone A) shown in 2.2a gives more credence to the possible existence of a fault F at depth, the other (zone A') shown in 2.2b gives more credence to the seismicity data.

3. ESTIMATION OF SEISMICITY PARAMETERS

3.1 Introduction

Since the initial elicitation of zonation and seismicity information we have been investigating the issue of estimating the seismicity in the EUS. There are several ways of developing estimates, including:

1. Relying solely on the historical data and mathematical models.
2. Relying solely on personal opinions based on each individual's analyses of the historical data and other sources of information on seismicity.
3. Using personal opinions as "prior" information in the analyses of the historical data with the mathematical models and data analysis being the principal elements in the estimation process.
4. Describing the historical data, analyzed in a uniform way, to experts for their use in formulating individual estimates of seismicity.

Relying solely on the historical data (method 1 above) is not a good procedure, particularly for the EUS, because of the sparsity of events and the incompleteness of the catalogs. Method 3 has the disadvantages that (1) most methods assume the "prior" information is independent of the data, which is unlikely to be the case for earthquakes, and (2) it still relies heavily on the mathematical models used in the analyses. We used method 2 in the initial elicitation which resulted in considerable variation between opinions. This is not necessarily bad, however we think that some of this variation might be artificial. That is, it does not necessarily reflect true differences of opinions, but is a result of differences in resources, particularly with regard to analyzing the historical data. With this in mind we have developed a method for analyzing the historical data to estimate seismicity. We propose to use this method to estimate the seismicity for each zone in your zonation maps. These estimates will be provided to you to help you develop your estimates of seismicity. The process is customized since it will depend on

your choice of a catalog as well as some estimate of model parameters which you will be asked to provide.

We do want to emphasize that in doing this it is not our intention to have you be unnecessarily influenced by these estimates but, rather, to provide a level of information about historical seismicity which is uniform to all individuals. Everyone is free to use these estimates to the extent they desire. You are encouraged to formulate your opinion no matter how close or deviant it may be from the historical record. Again, we emphasize that the LLNL approach is to base predictions of the seismic hazard on the opinions of knowledgeable individuals. We continue to be dedicated to this approach for characterizing the seismicity of the EUS and estimating the resulting hazard.

3.2 Estimation of Seismicity Based on Historical Data

Two significant problems related to using a catalog of historical events as a basis for estimating the seismicity of a region are:

- The incompleteness of the catalog, particularly for low magnitude earthquakes which occurred in the earlier years.
- The lack of distinction between foreshocks, main shocks, aftershocks, clusters, etc. in the catalog.

In addition, most of the recorded early events are described by intensity which is a subjective scale not intended to provide a "precise" estimate of the magnitude of an earthquake. Intensity, recorded in discrete units, should not be used in the same way as the magnitude measurements based on instrumentation data taken on a "continuous" scale.

The method we have developed to estimate seismicity using the historical data recognizes these difficulties and attempts to model the available data in a way which accounts for these constraints on the information available through

the historical records. We fully realize that our models are simple and cannot model reality completely. However, we emphasize again that the purpose is to provide everyone with a description of historical seismicity developed in a uniform manner. Under no circumstances are the results of the analyses intended to be the final answers.

The method is based on using the historical record of earthquakes of at least a magnitude 3.75 (m_b) in each zone to estimate the coefficients (a,b) in the classical recurrence model for the expected number $\Lambda(m)$ of events of magnitude m or greater per time period, i.e.. the relation

$$\log_{10}\Lambda\,(m) = a + bm \qquad (3.1)$$

This model is adjusted to account for the lower magnitude of interest, 3.75, and the upper magnitude cutoff M_U for each zone.

The basic assumption of the estimation process is that the recordings in a catalog represent, for each zone, a realization of the random occurrence of earthquakes over the period of the catalog subject to the constraint that given an earthquake occurs, there is a probability $\Pi_z(m,t)$ of it being detected and recorded. That is, an earthquake is not necessarily recorded with certainty. This provides a method for handling incompleteness of earthquake catalogs. As suggested by the notation, the probability of detection can vary between zones and depends on magnitude and time of occurrence, expressed in <u>years since the present</u>. We have modeled the probability of detection, as a function of magnitude and time, by

$$\Pi_z(m,t) = H(m)\,\exp\left[-\delta_z\,(M_D - m)^{\alpha_1}\,t^{\alpha_2}\right] \qquad (3.2)$$

where

- o H(m) is the probability of detecting, and recording, an earthquake of magnitude m <u>today</u> (based on the current capability of available EUS networks), if it occurred.
- o M_D is the smallest magnitude earthquake which would have been detected, and recorded, with certainty during the entire period covered by the catalog.
- o The parameters
  - o (α_1,α_2) are <u>shape</u> parameters which determine the general shape of the probability curve as a function of magnitude and time
  - o δ_z is a, potentially, zone dependent <u>scale</u> parameter which scales the probability curve over the range of magnitudes and times.

To minimize our influence on the estimates of seismicity, we propose to customize the model for incompleteness to each individual, thus we will be eliciting some necessary information from you. The fundamental approach to modeling the probability of detection is to have you suggest the "shape" of the probability curve (i.e., indirectly indicate appropriate values for (α_1,α_2))and to use the available data in a catalog to estimate a value of the "scale" parameter δ_z for each zone. In addition, we will ask you to indicate values for H(m), the probability of detecting a magnitude m earthquake today, if it occurs, and M_D, the smallest magnitude event detected with certainty throughout the catalog period.

The best way, we believe, to approximate the "shape" of the probability of detection, as a function of magnitude and time, is for you to identify a pair of magnitude, time combinations which have equal probability of detection. For example, you might consider a magnitude 6.5 event 120 years ago (in 1866) to have had the same probability of being detected as a magnitude 4.0

earthquake 30 years ago (in 1956). That is, you consider the magnitude-time combinations (6.5, 120) and (4.0, 30) to have the same probability of detection and inclusion in the catalog. We have found that setting α_2= 2.0 and allowing α_1 to be determined by the pair (m_1,t_1), and (m_2,t_2), works well and leads to "acceptable shapes" for the probability of detection curve. Thus you will be asked in Question 4.7 for these magnitude-time combinations.

Another issue of concern in estimating seismicity from historical data is the lack of distinction between foreshock, mainshocks, aftershocks, clusters, etc. in a catalog and the impact of culling some events from a catalog prior to estimating seismicity. There is no universal agreement on the issue of whether a distinction should be made nor if it is appropriate to distinguish between the different events and what and how to cull events. Therefore for our methodology we assume the catalog has been adjusted, if appropriate, prior to use as a data base for estimating seismicity. This issue is discussed further in Section 3.4

Finally, the methodology depends on having an estimate of the "true" magnitude of the earthquake, based on the m_b scale. Since not all events are recorded on the m_b scale it is necessary to transform non-m_b magnitudes and intensities to m_b. This is done as follows:

- o Measured m_b's are assumed to be unbiased estimates of the true magnitude.
- o For any magnitude scale m*, e.g. M_s the surface wave magnitude, a linear relation with true magnitude m_b is assumed, i.e..

$$m^* = c_{m^*} + d_{m^*}\, m_b + E \qquad (3.3)$$

where E is an error term which reflects the random variation of m* and the coefficients c_{m^*}, d_{m^*} are either

- assumed known

- estimated from the subset of events within the catalog for which both m* and measured m_b are recorded

o For intensities, an empirical distribution of magnitudes is estimated from the historical data for each discrete intensity integer, i.e.. the probability that the true magnitude is less than or equal to m, as a function of m, given an intensity, is estimated.

The recorded measurements in a catalog are transformed into an estimate of the true magnitude using the appropriate model, Eq. 3.3, if the record is a magnitude, or the empirical distribution of magnitude, if the record is an intensity. This data is then used to estimate the expected number of earthquakes in 272 bins covering the magnitude range-time period represented in the catalog. A model for the expected number of earthquakes per bins, involving the seismicity and probability of detection parameters, in based on the appropriate distributions for these counts. The method of maximum likelihood is used to estimate these parameters.

3.3 Earthquake Catalog

As indicated in the above discussion, to assist you in arriving at the seismicity parameters for each of your zones we will, as we did for (Q2), provide you a listing of the earthquakes in each zone. In addition we will also provide you with an estimate of the a,b-values for each of your zones using the uniform approach we developed. At the time of (Q1) and (Q2) the only catalog we had available as a default catalog was the "LLNL Catalog". Now we can offer you a listing of the earthquakes by zone based on either the LLNL catalog or the EPRI catalog. As before, you can also ask us to use some other catalog, however you will have to send it to us. In Question 4.4 you will be asked to identify which catalog you wish us to use. As the sorting process takes considerable effort we can only offer to sort one catalog.

We also want to once again emphasize that the selection of a catalog will not commit you to the use of that catalog for your final assessment of the seismicity parameters. As before, in making your assessments you should use any combination of catalogs and other information that, in your opinion, is most reliable for arriving at the seismicity parameters for each of your zones.

LLNL Catalog

The current form of the LLNL catalog is basically the same as the version we used to provide you the sorted earthquakes in Q2. However, we have now eliminated a few duplicate events which had been previously inadvertently left in the catalog.

The LLNL catalog is based on merging a number of catalogs. Because of the space and time overlap between the different catalogs, this resulted in multiple entries for the majority of the earthquakes listed. To edit the catalog, the following criteria were applied.

1. The entry from the local investigator was considered the most reliable and consequently was retained in the listing (e.g., for an event in southern Illinois, the SLU data were used).

2. In border regions (e.g., between the SLU and BOL areas or between the SLU and WES areas), the SLU data were selected.

3. For the remaining events, if there was an EQH listing, that data was retained.

4. There was a significant number of events remaining with a listing in the EUS catalog only. Each of these events was examined separately. If the evidence indicated that the event should have been contained in other catalogs (e.g., an intensity VII in a populated area) and it was not, the earthquake was removed from our composite catalog. This still left a

number of EUS events, (usually low intensity) the existence of which could not be confirmed. These events were retained in the catalog.

5. For the northeastern U.S., we adopted the magnitude estimates developed by Street and Lacroix (BSSA, Vol. 69 pp. 159-176) and changed the appropriate entries in the catalog.

EPRI CATALOG

At this time there is no document describing the make-up and the criteria used to finalize the EPRI catalog. Basically the EPRI catalog is formed by merging many catalogs, including the LLNL catalog. It is our understanding that all events of $m_b \geq 4.5$ ($I_o \geq 5.5$) were examined in detail. Smaller events were examined on a regional basis by one of their six Tectonic Evaluation Contractors (TECs). The TECs and other consultants met and developed a "consensus" (preferred entry) for each larger event. This formed a basis for the entries listed as preferred events. In some cases the consensus catalog differs significantly from the original catalogs. Our sensitivity studies indicate that there are about 30% fewer events of $m_b \geq 3.75$ (only considering preferred entries) in the EPRI catalog than in the LLNL catalog. It should be noted that virtually all of the entries in the LLNL catalog are in the EPRI catalog, however some are not considered as the preferred entry. This is an important distinction. Because of time and budget limitations we will limit the sorting to just the preferred entries.

EPRI also performed a detailed earthquake cluster analysis and denoted each earthquake as either a main event or a secondary event. An approach was developed by Veneziano and Van Dyck (1985) to statistically discriminate between main events and dependent events. The procedure is based on locating events clustered together in time and space. The test to determine if a given set of events represents a cluster is based on a local departure from stationarity and homogeneity of the assumed Poisson process of main events. The details are given in Veneziano and Van Dyck (1985).

3.4 Identification of Aftershocks

After major earthquakes there are often a sequence of smaller earthquakes the occurrence frequency of which appears to decay rapidly in time. The recurrence model for such sequences appears to have a different b-value than the longer historical record/and or regional data. It is often suggested that these events should be removed from the data set used to estimate the a and b-values for a seismic hazard analysis. Considerable judgment is required to determine which events fall into the category that should be removed. As a first step in the identification of events that should be removed from the catalog, it is helpful to have a listing of earthquakes which are clustered together in time and space. In order for us to provide you with such a listing, for your use in the identification of dependent events, we will need some input from you relative to the size of the window in time and space, as a function of the magnitude of the largest events in the cluster, that should be used to develop these cluster sets. In question 4.9 we ask for this information. We will send you the cluster sets after we receive your responses to Questions 4.8-4.10.

3.5 References for Section 3

Veneziano, D and Van Dyck, J (1985) Seismic Hazard Methodology for Nuclear Facilities in the Eastern United States, Vol. 2, EPRI Research Project P101-29.

QUESTIONNAIRE Q7

ZONATION QUESTIONS

4. QUESTIONS

4.1 Introduction

Your responses to questions 4.8, 4.9 and 4.10 in Section 4.4 are very important and need to be answered and sent to us immediately if possible. Then we can start the cluster analysis for the identification of aftershocks which is the first step in the sorting, and the seismicity calculations specific to your maps and catalog. This will enable us to develop the questionnaire Q8 in due time. You may wish to take more time to respond to the remaining questions in this questionnaire.

We have also included, for your information, in this package the original maps you sent us, new blank maps, computer generated maps from our digitization process based on your previous maps, tables A1 and A2 giving your previous degree of belief in the existence of each zone, what happens to zones which have degrees of belief less than unity and alternative boundary shapes and the degree of belief you gave for these shapes.

4.2 Questions Dealing with Zonation Maps

Question 4.1

Please update your maps as appropriate. As noted, your original maps are enclosed for your review and use for the revision. Please indicate your modifications clearly (using different colors and a clear key). Feel free, however, to use a new blank map (s) if your modifications are extensive. In any case, please return the original maps together with your responses to this questionnaire.

In revising your zonation maps please review critically your responses to Questionnaires 1 and 5 regarding the identification of seismic source zones in the Eastern United States. Please review your definition of the complementary zone. There is one issue you also might want to consider in your review. Our analyses have always assumed that an earthquake of magnitude 3.75 (m_b) or greater is possible throughout the entire EUS. Do you believe there are regions in the EUS in which it is not possible for a 3.75 or greater event to occur? In describing your uncertainty about seismicity-aseismicity of a zone, you may use either one of two techniques available Existence-non existence probability-zone replacement or alternate shape with different (i.e.. zero) seismicity.

Question 4.2

Please update Table A1, on your confidence in the "existence" of each zone, as appropriate.
Note* Table A1 is given at the end of this section.

Question 4.3

Please update Table A2, on alternative boundary shapes for individual zones or clusters of zones and your associated confidence, as appropriate.
Note* Table A2 is given at the end of this section.

4.3 Inputs for Estimating Seismicity Based on Historical Data

As part of the process of estimating seismicity using the historical data it is necessary to estimate the "true" magnitude from the measured magnitudes recorded in a catalog. To do this we must model the relationship between each magnitude scale and m_b as in Eq. (3.3). You can provide this or the

Historical data can be used to estimate this relationship. Or alternatively you can provide some of the relations and specify that the data be used to

determine the other relations. For example there are relatively few M_L values in the catalog that also have m_b estimates as well, hence you might want to specify this relationship. On the other hand, the catalogs have a number of entries for M_S that also have a m_b listed, hence for these you might want to let the data specify the relation to the m_b scale. The LLNL catalog has only M_L, m_b,and $M_S$entries. The EPRI catalog has entries for, m_b, M_S, m_{bLg}, M_C and M_N. M_C is a coda magnitude and M_N is listed as "Nuttli magnitude" (various definitions). In question 4.7 you will be asked to choose a catalog for our use, hence you only need to provide relations for the magnitude scales contained in the catalog of your choice.

Question Q4.4

Please indicate the catalog you would like us to use to estimate the seismicity of the zones you identify in your zonation maps:

Catalog Name: ______________

For each of the magnitudes included in the catalog of your choice indicate in Table 4.4, below:

- o that the catalog data should be used to estimate the relationship between each magnitude and m_b, i.e. check column 5 of Table 4.4

or

- o your estimates of the relationship between each magnitude and m_b by estimating c*,d* and the standard deviation associated with the magnitude.

1	2	3	4	5
m^*	c_{m^*}	d_{m^*}	E	Use Historic Data to Estimate
M_s				
M_L				
m_{bLg}				
M_n				
M_c				

where

$$m^* = c_{m^*} + d_{m^*}\, m_b + E$$

and E is described by the standard deviation of the random variable m*.

Note: The catalog you select, as answer to this question should be the same as your answer in question 4.8.

Question 4.5

It is also necessary to have an estimate of the standard deviation associated with the measured m_b scale. Please indicate your estimate

Before 1940 __________

Between 1941 - 1963 __________

After 1964 __________

Question 4.6

The distribution of earthquake magnitudes depends on the upper magnitude cutoff, M_U, for each of the zones. Please indicate (possibly update), in the appropriate column in Table A1, your best estimate of M_U for each of the zones you have identified on your zonation maps.

Question 4.7

Development of the detection probabilities for modeling incompleteness of a catalog requires estimates of the following parameters:

1. The smallest magnitude (on the m_b scale), M_D, which would have been detected with certainty over the entire time period of the catalog.

2. The probability of detection, H(m), as a function of magnitude, of events today. For convenience, this probability is assumed constant over half m_b units, e.g. from 6.25 to 6.75.

3. Two pairs of a magnitude-time combinations, which have equal probability of detection. One pair should be (high magnitude a long time ago) combination , e.g. (6.5, 200), and the second pair should be (lower magnitude a short time ago) combination, e.g. (5.5, 5.0).

Your opinions about these parameters can be given <u>either</u> for the entire EUS, for the four regions (NE, NL, SC, SE) or for each zone by filling either one of the three tables 4.7a, or 4.7b or 4.7c respectively. (Choose only <u>one</u> table)

1. For the entire

M_D	H(m) - Probability of Detection at present									Points of Equal Probability of Detection	
	3.75, 4.25	4.25, 4.75	4.75, 5.25	5.25, 5.75	5.75, 6.25	6.25, 6.75	6.75, 7.25	7.25, 7.75	7.75, 8.25	(m_1, t_1)	(m_2, t_2)

2. For the four regions: Table 4.7b

Region	M_D	H(m) - Probability of Detection at present									Points of Equal Probability of Detection	
		3.75, 4.25	4.25, 4.75	4.75, 5.25	5.25, 5.75	5.75, 6.25	6.25, 6.75	6.75, 7.25	7.25, 7.75	7.75, 8.25	(m_1, t_1)	(m_2, t_2)
NE												
NC												
SC												
SE												

3. For each zone: Table 4.7c

Zone	M_D	H(m) - Probability of Detection at present									Points of Equal Probability of Detection	
		3.75, 4.25	4.25, 4.75	4.75, 5.25	5.25, 5.75	5.75, 6.25	6.25, 6.75	6.75, 7.25	7.25, 7.75	7.75, 8.25	(m_1, t_1)	(m_2, t_2)

For each zone: Table 4.7c (continued)

Zone	M_D	H(m) - Probability of Detection at present									Points of Equal Probability of Detection	
		3.75, 4.25	4.25, 4.75	4.75, 5.25	5.25, 5.75	5.75, 6.25	6.25, 6.75	6.75, 7.25	7.25, 7.75	7.75, 8.25	(m_1,t_1)	(m_2,t_2)

For each zone: Table 4.7c (continued)

Zone	M_D	H(m) - Probability of Detection at present									Points of Equal Probability of Detection	
		3.75, 4.25	4.25, 4.75	4.75, 5.25	5.25, 5.75	5.75, 6.25	6.25, 6.75	6.75, 7.25	7.25, 7.75	7.75, 8.25	(m_1,t_1)	(m_2,t_2)

For each zone: Table 4.7c (continued)

Zone	M_D	H(m) - Probability of Detection at present									Points of Equal Probability of Detection	
		3.75, 4.25	4.25, 4.75	4.75, 5.25	5.25, 5.75	5.75, 6.25	6.25, 6.75	6.75, 7.25	7.25, 7.75	7.75, 8.25	(m_1,t_1)	(m_2,t_2)

For each zone: Table 4.7c (continued)

Zone	M_D	H(m) - Probability of Detection at present									Points of Equal Probability of Detection	
		3.75, 4.25	4.25, 4.75	4.75, 5.25	5.25, 5.75	5.75, 6.25	6.25, 6.75	6.75, 7.25	7.25, 7.75	7.75, 8.25	(m_1,t_1)	(m_2,t_2)

4.4 Questions Dealing with Catalogs and Aftershocks

Question 4.8

Which catalog shall we use to provide you a listing of the earthquakes in each of your source zones and an estimate of the a and b-values?

LLNL Catalog __________ **EPRI Catalog** ____________

Other ___________

If other, then we will need a copy of the catalog either in magnetic tape or on punched cards.
*Note that the choice of a catalog should be the same as your answer in Question 4.4.

Question 4.9

Please supply the magnitude dependent windows in time and space to use to define the clusters in the catalog for your use in aftershock identification If you have selected the EPRI catalog and want to use the identification of main events-dependent events made by EPRI, or if you have selected the LLNL catalog and want to use the identification main events- dependent events described in Section 4.3 of Bernreuter et al. (1986) already sent to you under seperate cover, go to question 4.10.

Magnitude range (m_b)	Time Window (days)	Distance Window (km)

Note a circular distance window will be used.

Question 4.10

If you have selected either the EPRI or LLNL catalogs and want to also use the results of the EPRI or LLNL studies which identified dependent events. Check here _________.

EIGHTH QUESTIONNAIRE

SEISMICITY INPUT DOCUMENTATION (Q8)

EIGHT QUESTIONNAIRE
SEISMICITY INPUT DOCUMENTATION (Q8)

1. INTRODUCTION

The primary goal of the Eastern U.S. (EUS) seismic hazard characterization project is to describe the seismicity throughout the EUS. This description is to be used to realistically assess the seismic hazard at nuclear power plant sites throughout the region. In the first phase of this project we elicited your opinions about the zonation and seismicity of the EUS. Your opinions, combined with inputs from the panel on ground motion models, were used as inputs into the seismic hazard evaluation method developed for the project. The results were applied to 10 sites to demonstrate the feasibility of this approach to estimating seismic hazard.

The next phase of the project involves assessing the hazard at all nuclear power plant sites throughout the EUS. Prior to making these assessments we are doing two things:

- Re-eliciting your opinions about zonation and seismicity to give you an opportunity to update your estimates, if appropriate, in light of any recent information you may have been exposed to and to allow us to incorporate improvements into our methodology.

- Visiting with our panel members to explore with you the process you went through in formulating and reporting your opinions. This effort is in response to some criticisms we have received from reviewers of the project.

This document is intended to introduce you to our approach to documenting the bases of your subjective inputs on seismicity. In the text, you will find a series of questions to which you will be requested to respond to at the time of our one-on-one meeting with you. For convenience, we have also gathered these questions on fifteen separate pages at the end of this document.

2. NEED FOR DOCUMENTATION

In designing the elicitation process one of our guiding principles was to make sure that all experts had complete flexibility to develop their resources and opinions independent of the other panelists. We wanted everyone to function independently in formulating their opinions. Thus, we did not attempt to structure your line of thinking about the issues relevant to EUS seismicity. This allowed you the flexibility to use analytical methods as well as personal intuition and insight to the degree you felt appropriate. Overall, we wanted to assure that everyone could express their opinions without regard to a consensus being formulated among the participants. That is, we wanted everyone to feel free to express their opinions, even if they differed from the opinions of the other panelists. Thus, we wanted to be able to capture the range of opinions that might exist among knowledgeable individuals. We believe that the elicitation process has followed this principle.

In following this philosophy of eliciting opinions, we have not neglected the need to assure the quality of your inputs. We have introduced several quality assurance measures into the elicitation process:

- In the initial choice of experts for inclusion as panelists.

- As part of the development of the questionnaires used to elicit your opinions, careful consideration was given to the structure of the questions.

- By interacting with individuals to clarify potential misunderstandings.

- By having group discussions after the initial elicitation and following these with feedback questionnaires.

- By introducing qualitative and quantitative comparisons of your

inputs with available earthquake data, with subsequent clarification of significant discrepancies.

We are confident that these measures can assure the quality of the final seismicity inputs and the applicability of the resulting estimated seismic hazard.

In addition, the overall program was subject to peer review. A criticism by several members of this panel was the lack of documentation relative to the opinions of our experts. The reviewers felt that better control and documentation of the seismicity and ground model descriptions would add credibility to and facilitate verification of the results of the project. It was suggested, also, that documentation would help to reduce biases and eliminate inconsistencies in the opinions expressed by the experts. Other reviewers, e.g., AIF, EPRI, had similar criticisms. It has been argued that lack of documentation will make it difficult to judge when your present opinions will be outdated, i.e., opinions have changed significantly, so that an updated study should be done.

Also, the Panel on Seismic Hazard Analysis of the Committee on Seismology of the National Research Council (Ref. Private Communication from D.L. Bernreuter) has been discussing including "documentation of models and procedures" as an important element of a probabilistic seismic risk analysis.

To meet these criticisms and to ensure that our sponsors, the Nuclear Regulatory Commission, have a product which is credible and readily applicable to making decisions regarding the relative seismic risks to nuclear power plants located in the EUS, we are undertaking the task of developing additional substantiation of the inputs used in the seismic hazard analyses. To do this we need to explore with you your development of the zonation and seismicity parameter values you have provided.

We want to emphasize that our attempt at documentation is not a reflection of our confidence in the inputs you have provided. We are quite satisfied with the results that have been derived so far and are confident that your inputs have been carefully developed and are based on sound reasoning. Rather, we feel sufficiently confident in our methodology, both the elicitation of inputs and the seismic hazard analyses, that we want to do everything that we can (and still follow our underlying philosophy) to maximize the credibility and applicability of the results. We feel that some documentation of the process you went through in formulating your opinions will help in this regard.

3. PHILOSOPHY OF DOCUMENTATION

The purpose of this document is to serve as an introduction of our philosophy with regard to substantiation of your opinions, to indicate what we hope to derive from this exercise and how we plan to proceed with the documentation process.

In developing substantiation of the seismicity inputs we are not interested in detailed technical justification for each of your choices. Rather, we are interested in understanding "how" you arrived at your judgements, i.e., what is the general basis of your opinions. We recognize, of course, that the likely situation is that you used multiple sources and methods to develop your final opinions. We would like to document what your primary sources are and what methods, e.g, graphical, analytical, logical implications, you might have used.

To illustrate the type of information we are interested in, consider the issue of zonation. We are not interested in a detailed geologic/tectonic justification of why a given zone was selected at some location with a given boundary, e.g. because a known fault, running in a southwest-northwest direction, exists. Rather, we are interested in what type of information formed the basis for your zonation. For example, you might have used known features to identify specific zones and considered all other areas as part of

a background or complementary zone. On the other hand, you may have based your opinions on historical seismicity and developed your zones by identifying areas of homogeneous seismicity. Or, you might have identified known features in some areas and used historical seismicity in other parts of the EUS. Alternately, you may have used all these and other sources, e.g., "weighting" known features most heavily, historical seismicity secondary and geologic, stress processes and stress conditions as a minor contributor. Overall, we are interested in documenting your basic sources of information, any analysis you might have done and the thought process you went through to develop the zonation.

Similarly, for the seismicity parameter values several issues, that could have had a significant effect on your inputs, should be investigated, including:

- o Data sources you considered, e.g., a specific catalog, the data provided by LLNL, etc.
- o Your treatment of clusters, foreshocks, aftershocks and identification of a main shock, if appropriate.
- o Any adjustment for catalog incompleteness you may have made.
- o The methods for estimating the parameters (a,b) you used.
- o How you proceeded in making a prediction of the upper magnitude cutoff.

Finally, the issue of assessing and describing your uncertainty in your zonation and specification of the seismicity parameters needs to be explored. For example, what types of uncertainties did you consider when specifying the bounds for the seismicity parameters? What does the terminology "95 percent confidence or uncertainty bounds" mean to you?

Overall, we are interested in documenting, without going into minute details, the process you went through as you developed your opinions regarding EUS seismicity.

Our method of developing this documentation is to visit with you, conduct a one-to-one interview to explore with you your sources of information and methods of formulating your opinions, and then summarizing your inputs. Thus, we will not be asking you to write an extensive report, detailing justification for each zone and the precise values provided for the seismicity parameters. Rather, after the interview we will summarize, in a standard format, your process of developing opinions about EUS seismicity. These summaries, of course, are subject to your review.

The remaining sections will outline the key questions we will be discussing with you during the interview. By providing these questions, we hope that you will give them some thought prior to our visit with you so that we can make effective use of the dialogue during the interview. Also, if you feel it is appropriate to either make a list of your resources or have them available for our cataloging, this would be appreciated.

4. ZONATION

There are several sources of information one might use to develop a zonation of the EUS. One approach might be to use the physical characteristics of a region as a basis for developing source zones. Such characteristics include tectonic processes and stress patterns such as

- tectonic stresses
- variation in crustal thickness and density distribution
- other stress sources

or identifiable tectonic features such as

- faults
- basins
- plutons

or other physically identifiable discontinuities or non-homogeneities in the crust which might be potential sources of earthquakes. A second approach might be to rely on observational data such as maps of historical earthquakes including,

- o plots of epicenter "locations"
- o contour maps of numbers and magnitudes of post events
- o plots of seismic moments
- o plots of energy and strain releases

Other observable indicators of seismic activity might include geologic evidence, spatial and temporal changes in strength, evidence of local stress amplification or strain.

It is recognized that any single source of information is likely to be inadequate to identify all source zones, thus we imagine you used a combination of information sources as a basis for zonation.

Question 1 Discuss briefly the adequacy of the principal sources of information, including physical characteristics and observational data, as a basis for identifying source zones.

Question 2 Outline your principal bases for identifying zones. To what extent did you rely on tectonic and geophysical features as a source of zonation? What, if any, historical seismicity and other observational data did you consider in your development of seismic source zones?

Certainly many other factors, besides identification of areas of homogeneous seismic activity, affected your development of the actual zonation maps, such issues as the lower bound magnitude, $m_b = 3.75$ for this project might have influenced your choice of zones. Also, at the micro level no region is entirely seismically homogeneous so you always were confronted with perhaps a

scaling question-just how "fine" must the mesh of zones be to adequately characterize EUS seismicity? These, and other factors, required you to make many judgements in the process of developing your zonation maps.

Question 3 Identify some of the factors, such as the scale of resolution of your zonation maps, lower bound magnitude, which influenced your development of the EUS zonation maps. Rank the relative importance of each of these factors, and, if possible, explain how these factors influenced your choice.

The concepts of background and complementary zones were important components in adequately zoning the EUS and accounting for historical seismicity.

Question 4 Describe, briefly, the influence of, and your use of, these features in the development of your zonation maps.

Finally, there are numerous reasons for being uncertain about the identity of any specific zone or zones. You were given the opportunity to express your uncertainty in zoning specific areas by specifying, in terms of a probability,

- the likelihood of the "existence" of a zone or zones, i.e., the need to identify a zone as different from the surrounding region

- alternative zone boundaries

Question 5 Did you feel that these two ways of describing uncertainty provided you with adequate means of expressing your state of knowledge regarding zonation of the EUS? Discuss the types of uncertainties you had identified and attempted to model by specifying a probability of "existence" of a zone and/or alternative zone boundaries.

5. SEISMICITY

Given a source zone, i.e., an area of homogeneous earthquake activity, three parameters were identified to describe the seismicity of the zone. These are:

- The upper magnitude cutoff, M_U, i.e., the largest magnitude that can occur given the geologic/tectonic conditions of the zone.

- The intercept,a, and slope, b, of the magnitude recurrence model, where a is related to the occurrence rate of earthquakes within the zone and b is related to the parameter of the distribution of magnitudes amongst earthquakes.

We have asked you to provide estimates of these parameters, based on your assessment of the seismic conditions within each zone, in terms of:

- An interval to which you would associate some measure of confidence (we assumed 95 percent confidence) that it bounds the actual value.

- The most likely (called best estimate) value of each parameter.

Evaluation of these parameters involves some assessment of the historical data and/or the seismological conditions existing within a zone. We need to explore with you:

- your primary source of information regarding seismicity, and
- your overall approach to estimating the seismic parameters based on summarization of this information.

5.1 Upper Magnitude Cutoff

The largest magnitude earthquake that can occur within a source zone is a difficult parameter to estimate, particularly in a region, such as the EUS, where only a limited number of events have been recorded.

Several procedures have been considered for estimating the largest magnitude event that can occur within a zone. Again, one approach is to use physical properties, such as fault length, rupture area, stress drop or other tectonic characteristics, to predict maximum magnitude. Alternately, analyses of the historical data might be used as a basis of estimating M_U. For example, a plot of the number of events exceeding m_b versus m_b may display a sharp drop at some value, indicating, perhaps, some limit on the size of earthquakes in that zone. A very simple approach might be to use the largest magnitude observed plus some increment. Of course, any analytic approach might be tempered by physical constraints, e.g., limitation on the measurement scale, or subjective input, e.g., conviction that any region is capable of producing a $m_b \geq 5.0$.

Question 6 Discuss briefly what type of uncertainties you considered when specifying the bounds for the seismicity parameters.

Question 7 What does the terminology "95 percent confidence or uncertainty bounds" mean to you? How did you interpret it?

Question 8 Discuss, briefly, the significant issues related to predicting the largest magnitude earthquake that can be expected to occur in a source zone.

Question 9 Outline, briefly, the sources of information which formed the basis for your predictions of the largest magnitude.

Question 10 Did you follow a consistent procedure for predicting M_U? If so, briefly outline the procedure. Were you influenced by any constraints, e.g., limits of measurements scale, when considering your estimate?

Question 11 What are the primary sources of uncertainty that you were trying to describe in determining the upper and lower limits for M_U?

5.2 Magnitude Recurrence Model Parameters

Traditionally, the seismicity within a source zone has been based on modeling the magnitude recurrence relationship by the linear model

$$\log N(m) = a - bm$$

with N(m) being the number of earthquakes with magnitudes exceeding m, and where the model is frequently adjusted to recognize the finite upper magnitude cutoff. The coefficients (a,b) vary between zones and are the unknown parameters which must be estimated.

Various methods for estimating (a,b) may be considered but perhaps the most common procedure is to use the historical data as, at least, an initial basis for evaluating these coefficients. Any analytical procedure for estimating (a,b) using the available catalogs of recorded earthquake in the eastern U.S. must take into consideration the quality of historical data. Two issues frequently raised with regard to the use of existing catalogs are:

- o the existence of clusters, foreshocks and aftershocks within the catalogs and,
- o the completeness of the catalogs over time, locations and magnitudes

Several procedures, both analytical and empirical, have been considered and developed to adjust for aftershocks, etc. as well as incompleteness of the catalogs. One such procedure, referred to as the "uniform approach to estimating (a,b)" was developed by LLNL for the second phase of the elicitation process. This procedure relies on an empirical adjustment for aftershocks, clusters, etc. but analytically adjusts for incompleteness by introducing a probability of detection as a function of time and magnitude for

each source zone. Other procedures have been developed which also rely on analytical procedures for indentifying and eliminating aftershocks, clusters, etc. For all of these efforts, there are still some underlying questions. For example, even though mathematical model, the Poisson model, used in the hazard analysis does not properly model clusters, aftershocks, etc., is it appropriate to remove these events from the catalog? Also, just how well can catalog incompleteness be modeled by introducing the concept of a probability of detection? These issues, and others, certainly must have been of concern to you as you developed your estimates of (a,b).

Question 12 Discuss, briefly, the various issues, e.g., clusters, catalog incompleteness, related to using recorded earthquake data as a basis for estimating the seismicity parameters (a,b).

Question 13 Outline, and rank, the principal sources, e.g., analysis based on your chosen catalog, the results of the LLNL "uniform approach", you used to develop your estimates of (a,b).

Question 14 If you used a catalog of recorded events as a basis for estimating (a,b), to what extent did you use analytical procedures to adjust for the aftershocks, etc and for incompleteness? Give a brief description of these procedures.

Many other issues, e.g. an underlying inclination that b should be approximately 1.0, the parameters (a,b) should be spatially "smooth" and /or could vary within a zone, are subject to considerable differences of opinions among knowledgeable individuals.

Question 15 Identify and discuss, briefly, some of the significant issues impacting characterization of the seismicity of the EUS.

Finally, there is again the issue of the uncertainty associated with predicting these seismicity parameters. An added complexity in this case is

that one must consider the concept of correlation,i.e. a possibly joint uncertainty. Stated another way, ones uncertainty about the value of one of the parameters depends on the value of the second parameter. If ones prediction of (a,b) was based on a statistical analysis of the historical data alone, the resulting estimates of (a,b) would be correlated. However, if empirical judgement is used in the ultimate predictions, it is quite possible that ones state of knowledge about one parameter, e.g. about b, would not depend on the value of the other parameter. Then, with regard to uncertainty, a and b are independent.

Question 16 What do you consider to be the major sources of uncertainty in predicting the seismicity parameters (a,b)?

Question 17 Were the alternates presented in the seismicity questionnaires for modeling potential correlation between (a,b) adequate for you to express your views about your joint uncertainty about the seismicity parameters? Discuss your views on correlation between a and b.

NINTH QUESTIONNAIRE - SEISMICITY Q9

NINTH QUESTIONNAIRE
SEISMICITY Q9

1. INTRODUCTION

The emphasis in this questionnaire is to elicit your current opinions about the seismicity associated with each of the source zones you identified on the zonation maps you provided in response to Feedback Questionnaire Q7.

As discussed in Q7, several seismic events have occurred recently and considerable activity, both research and applications, has occurred in all fields related to seismic hazard analysis. The EPRI (1986) effort, for example, is an important source of tectonic and geophysical information relevant to the EUS as well as providing new insights into seismicity interpretations. All of these might be cause for you to rethink your opinions about EUS seismicity. In any case, we want to elicit your current opinions prior to evaluating the seismic hazard at locations beyond the ten sites considered during the initial phases of this project.

In addition, as described in Q7, we have developed a method, using a catalog of historical earthquakes, to estimate the seismicity within a source zone, i.e. to estimate the parameters (a,b) of the magnitude recurrence model. Using your inputs relevant to modeling a detection probability and adjusting a catalog for clustering, foreshocks and aftershocks, we have estimated, based on the recorded earthquakes in the catalog you asked us to use, the parameters (a,b) of the recurrence model for each of the source zones you identified. These estimates are included in the packet of information sent with this document.

In providing these estimates, we are not trying to unduly influence your opinions nor bias your estimates of seismicity. We are motivated by our desire to provide everyone with as much information as possible to assist you in formulating your opinions. You can use these inputs to the extent that you

feel they are a useful source of information. They should be combined with your other sources of seismicity information as well as with your professional judgements and instincts in formulating your final opinions. Again, we want to emphasize that the basis of the seismicity data base that is to be used in the seismic hazard analysis are your opinions. Thus, our basic approach to characterizing EUS seismicity remains the same as it has been throughout the project.

Finally, we were disappointed with the models we used to describe the correlation in your estimates of the seismicity parameters (a,b). Thus, we have redesigned these models. We believe the revised models will give you a better opportunity to express the "joint" uncertainty you have in the (a,b) estimates. These models are discussed further in Section 2.4.2.2.

2. ELEMENTS TO BE UPDATED: SEISMICITY

2.1 Introduction

The topics on seismicity in this questionnaire are the same as in the previous questionnaires on seismicity, Q2 and Q5. The information we are eliciting from you are your estimates of the seismicity parameters, i.e.:

- o the upper magnitude cutoff M_U for each source zone
- o the parameter (a,b) of the magnitude-recurrence model, within each source zone

As before, we will ask you to express your opinions in two ways by providing (1) a most likely value (called best estimate) of each parameter and (2) two bounds which you are confident (we treat your level of confidence to be 95 per cent) include the true value of the parameter. Again, your bounds should reflect your confidence in the sources of information available to you for formulating your opinions. That is, they should quantify your state of knowledge and/or your level of uncertainty about the true value of the parameter.

In the following sections we discuss the topics of the seismicity update, review some of the important issues relevant to assessing seismicity and introduce the questions we will ask you to respond to.

2.2 Upper Magnitude Cutoff, M_U

Although you were asked to estimate the upper magnitude cutoff for each of your source zones in Q7, for completeness we will be asking you to provide those estimates again along with limits for M_U which you are confident include the true upper magnitude cutoff. Again, the bounds should reflect your confidence in the sources of information used to estimate M_U. Conversely, the bounds should quantify your uncertainty in estimating the upper magnitude

cutoff. The width of the interval between the lower bound M_{UL}, and the upper bound M_{UU} should depend on the amount of information you have at your disposal and/or how much that information provides a clear indication of the value of M_U. Good quality information should be associated with narrow limits while limited or questionable data should be reflected in wider limits. As a reminder, we associate a 95 percent level of confidence to your bounds for M_U in developing the "uncertainty bounds" for the seismic hazard at a site.

Your estimates of M_U should be included as an entry in Table 2.

2.3 Magnitude-Recurrence Model

Recognizing that perhaps we are somewhat redundant in asking you again to choose between (1) the LLNL model and (2) a truncated exponential model, we still feel it is necessary to give you the opportunity to reconsider your initial choice of model. Thus, we will ask you to choose between the two models as part of this set of questions.

To ensure that you are aware of the distinctions between the two models, we will briefly describe each model and outline the differences between them.

A. LLNL Model:
The basic Model

$$\log_{10} N_m = a + bm, \qquad M_{LB} < m < M_{UB} \qquad (1)$$

where N_m is the expected number, per year, (occurrence rate) of events of magnitude m or greater. This model (1) is assumed to be applicable for magnitudes in the range (M_{LB}, M_{UB}). For magnitudes outside that range, the model is adjusted as follows:

o For $3.75 = M_o \leq m \leq M_{LB}$,

$$N_m = \alpha_o + \alpha_1 m + \alpha_2 m^2 \tag{2}$$

such that

$N_{Mo} = \lambda_o$, the occurrence rate of magnitude 3.75 or greater

and

$$\log_{10} N_{M_{LB}} = a + bM_{LB}$$

given the restriction $\text{Log}_{10} \lambda_o \geq a + b M_{LB}$

That is, the model is interpolated between M_o and M_{LB} by the logarithm of a quadratic equation, restricted to equal the estimated occurrence rate λ_o at the lower magnitude limit M_o.

o For $M_{UB} < m \leq M_U$,

$$N_m = \alpha e^{\beta m} (M_U - m)^2 \tag{3}$$

such that

$$\text{Log}_{10} N_{M_{UB}} = a + b M_{UB}$$

and where the condition $N_{M_U} = 0$ is satisfied.

The model is illustrated in Fig. 1.

B. Truncated Exponential Model

Based on modeling the distribution of earthquake magnitudes as a bounded exponential distribution on (M_O, M_U) and restricting the model to have the form

$$\log N_{M_O} = a + b\, M_O$$

at $m = M_O$, the magnitude-recurrence model can be expressed as

$$\log_{10} N_m = a + bm + \log_{10} \left[\left(1 - e^{-\beta(M_U - m)}\right) / \left(1 - e^{-\beta(M_U - M_O)}\right) \right], \quad M_O < m < M_U \tag{4}$$

where $\beta = -b \log_{10}^{-1} e$, is the parameter of the exponential distribution.

This model is illustrated in Fig. 2.

Although the model as expressed in Equation 4 assumes it is applicable over the entire range (M_O, M_U), it is possible to limit the model to magnitudes greater than some lower bound $M_{LB} > M_O$. In that case, we use the polynomial adjustment (as given for the LLNL model) for $M_O \leq m < M_{LB}$ and the model given in Equation 4 for $M_{LB} \leq m \leq M_U$.

In comparison, the LLNL model preserves the linearity of the magnitude recurrence relationship over a desired range (M_{LB}, M_{UB}), however it does have the feature that the expected number in some magnitude interval $(m, m + \Delta)$ may be less than the expected number in a comparable interval $(m', m' + \Delta)$ even if $m' > m$, i.e. the expected number is not always decreasing for high magnitudes close to M_U. This is due to the adjustment introduced for $M_{UB} < m < M_U$. On the other hand, the expected number does decrease smoothly as m increases and approaches M_U for the truncated exponential model. However, the linearity of the magnitude-recurrence relation is not preserved over any subinterval of

magnitudes. Values of the expected number exceeding magnitude m, N_m, and the expected number per 0.25 unit intervals, $N_{\Delta m}$, are given in Table 1 for comparison.

2.4 Magnitude-Recurrence Parameters (a,b)

Included with the questionnaire you will have estimates of the parameters (a,b), based on a statistical analysis of the cataloged information about past earthquakes located within each of your source zones. We hope that you will find these estimates to be useful inputs as you review and reconsider your estimates of the seismicity parameters (a,b) for each of your source zones.

So that you can judge the value of these estimates as a source of information about seismicity, the following is a brief description of the methodology used to assess the estimates of (a,b).

2.4.1 Outline of the "uniform method" for estimating seismicity parameters

The "uniform method" for estimating the seismicity within specified source zones uses, as input, a catalog of historical earthquakes which is assumed to have been adjusted per your request, if appropriate, to account for the effects of earthquake clusters, foreshocks and aftershocks. Thus, the catalog is assumed to be culled and to contain only earthquakes considered appropriate, by the user of the seismicity estimates, for describing seismicity within a source zone. The other assumptions which form the basis for the methodology are consistent with the models of EUS seismicity and seismic hazard used in this project. Specifically, the historical data is analyzed based on the assumptions:

(a) earthquakes occur temporally as a Poisson process
(b) earthquakes occur spatially at random within a source zones
(c) given an earthquake occurs, the magnitude is a random realization from a bounded exponential distribution with range (M_0, M_U), i.e.

Equation 4, is used as the model of the magnitude-recurrence relationship.

(d) given an earthquake occurs, there is a probability, p_D, called the "detection probability", that the earthquake is detected and recorded in the catalog. The probability, p_D, is assumed to be a function of magnitude, time and location (zone).

Since catalogs generally contain several measures of earthquake size, e.g. intensity, m_b, M_S,..., it is further assumed that

(e) there is essentially no difference between the M_{bLg}, m_b and m_L magnitude scales, hereafter denoted M_{bLg}.

(f) there exists a linear relationship between any other magnitude based measure, M, and the true magnitude, $M_b{}^T$, measured on the M_{bLg} scale.

(g) for any epicentral intensity, I_o, there is a distribution of true magnitudes which result in the recorded intensity I_o.

It is recognized, in making assumption (e), that this is only an approximation and that each of these scales has a unique definition. However, we find many inconsistencies between users of the different scales, particularly when recording events in catalogs. Thus, rather than try to be overly precise about a reference magnitude scale, we prefer to leave the magnitude scale somewhat vague. However, we will use the symbol M_{bLg} whenever we need to refer to a reference magnitude scale.

The latter assumption, (g), is necessary since intensity measurements are different from instrumentally based magnitudes. Intensity is based on visual observations and recordings of physical events beyond ground motion, e.g, buildings collapsing, furniture falling, etc. It is a subjective measure recorded on a discrete scale. It differs from magnitude measurements based on recording instruments. Thus, it is inappropriate to assume a linear model

describes the relationship between M_{bLg} and intensity. A plot of the recorded M_{bLg} values versus intensity is shown in Fig. 3 for the earthquakes in the LLNL catalog which have both intensity and M_{bLg} measurements included in the catalog.

Given these assumptions, initially either

(1) the linear relationships between magnitude scales are specified, if known, and used to estimate the true magnitudes ${M_{bLg}}^T$.

or (2) the events in the catalog for which two different magnitude scales are recorded are used to estimate the linear relationship. Estimation is based on maximum likelihood with the true magnitudes ${M_{bLg}}^T$ treated as unknown nuisance parameters.

Events for which intensity and M_{bLg} magnitudes are recorded are used to estimate the empirical distribution of ${M_{bLg}}^T$ given I_o, for each integer intensity level. This distribution is expressed by the probabilities $P_1(I_o)$, $P_2(I_o), \ldots, P_K(I_o)$ for K subintervals of the range of m_b given I_o. From this analysis, for each event, either

- o an estimate $\hat{M}_{bLg}{}^T$ of the true magnitude

or

- o a probability distribution $P_1, P_2, \ldots P_K$ over the M_{bLg} range given an intensity reading

is available for estimating the seismicity parameters.

For a given source zone, the number, $n(m_k, t_\ell)$, of earthquakes with magnitudes in subinterval $(m_k - \delta, m_k + \delta)$, $k = 1, \ldots K$, of the magnitude range $(3.75, M_U)$ that occurred (and were recorded) during the time period $(t_\ell - \Delta(\ell), t_\ell + \Delta(\ell)$, $\ell = 1, \ldots, L,)$ is assessed from the catalog. That is, the magnitude range and time period covered by the catalog are partitioned into K x L magnitude-time bins and the number, $n(m_k, t_\ell)$, of earthquakes occurring in

each bin is evaluated. If an event is recorded with an intensity measurement only, it contributes to several magnitude bins based on the empirical distribution P_1, P_2, ..., P_K.

Under the assumptions, $n(m_k,t_\ell)$ is a Poisson random variable with parameter

$$\lambda(k,\ell) = 2\ \Delta(\quad \lambda(k)\ p_D(k,\ell)$$

where $\lambda(k)$ is the expected number of earthquakes, within the zone, with magnitudes in the subinterval $(m_k - \delta,\ m_k + \delta)$ and $p_D(k,\ell)$ is the detection probability of events with magnitude in the k-th interval occurring during the ℓ-th time period. The parameter $\lambda(k)$ is based on the bounded exponential distribution of magnitudes and is given by

$$\lambda(k) = \lambda_o[e^{-\beta\ (M_{kL} - M_o)} - e^{-\beta(M_{kU} - M_o)}]/\ [1 - e^{-\beta(M_U - M_o)}]$$

where $M_o = 3.75$, (M_{kL},M_{kU}) are the end points of the k-th magnitude subinterval, λ_o is the expected number of earthquakes of magnitude M_o or greater and β is the unknown parameter of the exponential distribution.

The probability of detection $p_D(k,\ell)$ depends on location (the specific zone), the magnitude interval (M_{kL},M_{kU}) and the time period $(t_\ell - \Delta(\ell),\ t_\ell + \Delta(\ell))$. The functional model is assumed to have the form, for the z-th zone

$$p_{Dz}(k,\ell) = H(m_k)\ e^{-\delta_z\ (M_U - m_k)^{\alpha_1} |t_\ell - t_o|^{\alpha_2}}$$

where $(\alpha_1,\ \alpha_2)$ are inputs derived from your opinions (Q7) on the relationship between detection in recent times and detection in earlier times (see Q7 for a discussion of this relationship), $H(\cdot)$ is a specified function of magnitude which allows for imperfect detection (and recording) today, i.e. at time t_o,

the latest time covered by the catalog, and δ_z is the location (zone) effect which is estimated from the data in the catalog.

The data, $n(m_k, t_\ell)$, along with the inputs (α_1, α_2) and $H(\cdot)$, are used to estimate, based on the maximum likelihood method of estimation, the unknown parameters δ_z, λ_o, β. Estimates of the seismicity parameters (a,b) of the usual magnitude-recurrence model

$$\log N_m = a + b\,m$$

are

$$\tilde{a} = \tilde{\lambda}_o$$

$$\tilde{b} = \tilde{\beta} \log_{10} e$$

where $\tilde{\lambda}_o$, $\tilde{\beta}$ denote the estimates of λ_o, β.

This method was developed for the purpose of providing everyone with estimates, based on the historical data, of seismicity derived from a uniform analysis. We hope you find these estimates useful and helpful in formulating your opinions about seismicity. Again, we point out, however, that the emphasis of this project is to have you evaluate and submit your opinions based on your judgements and all information you have available.

2.4.2 Uncertainty in (a,b)

2.4.2.1 Uncertainty range for (a,b)

Just a brief note to again reiterate (Ref. Q5) how the range of uncertainty in (a,b) affects the range of uncertainty in N_m, the expected number (per year) of earthquakes with magnitudes m or greater.

The magnitude-recurrence model describes the relationship between the logarithm of the expected number and magnitude, i.e.

$$\log_{10} N_m = a + b\,m$$

adjusted, of course, for the truncation of the magnitudes at the upper magnitude cutoff. Thus,

$$N_m = 10^{a + bm}$$

To describe the effects of uncertainty in the parameters (a,b), consider the case of symmetric uncertainty bounds, $(\hat{a} \pm \Delta a)$, and $(\hat{b} \pm \Delta b)$, for a and b respectively, and assuming that the uncertainties in (a,b) are independent. In this case the uncertainty in N_m can be expressed by

$$\left(\frac{1}{f}\hat{N}_m\ ,\ f\,\hat{N}_m\right)$$

where $N_m = 10^{\hat{a} + \hat{b}m}$ is the most likely value and

$$f = 10^{\Delta a + \Delta bm}$$

which can be partitioned into the contribution $10^{\Delta a}$ due to the uncertainty in a and the portion $10^{\Delta bm}$ due to the uncertainty in b. Thus, a half unit uncertainty in a, i.e., $\Delta a = 0.5$, corresponds to a factor of 3.16 uncertainty in N_m. On the other hand, the uncertainty in N_m due to the uncertainty in b changes with magnitude, increasing as m increases. For example, a 0.1 uncertainty in b i.e $\Delta b = .1$ at $m_b = 3.75$ corresponds to a factor of 2.37 uncertainty in N_m at $m_b = 3.75$ but a factor of approximately 4.22 at $m_b = 6.25$. For $\Delta a = 0.5$ and $\Delta b = 0.1$, the overall uncertainty factor varies between $f = 7.5$ at $m_b = 3.75$ and $f = 13.34$ at $m_b = 6.25$, almost a factor of 2 increase over the magnitude range (3.75, 6.25).

Whether the estimates of (a,b) are independent or correlated also impacts how the uncertainty in the seismicity parameters translates into uncertainty in the expected numbers N_m. For example, suppose the estimates of the seismicity parameters were:

Most likely values: $\hat{a} = 2.9$, $\hat{b} = -0.9$
Uncertainty bounds: $a_L = 2.6$, $a_U = 3.2$, i.e. $\Delta a = 0.3$
$b_L = -0.93$, $b_U = -0.87$, i.e. $\Delta b = 0.03$

This level of uncertainty in the seismicity parameters corresponds to uncertainty bounds for N_m, assuming the estimates of (a,b) are independent (i.e., uncorrelated) or "perfectly" correlated, as follows:

	Bounds on N_m for (a,b) Uncorrelated	Bounds on N_m for (a,b) Perfectly Correlated
m_b = 3.75	(.130, .866)	(.218, .516)
6.25	(.0006,.0058)	(.0015, .0024)

That is, the uncertainty intervals, under the correlated model, are narrower than those under the uncorrelated model.

If you have not considered the effect of the uncertainty in (a,b) on the uncertainty in N_m we would encourage you to consider this as you review your estimates of seismicity and the uncertainty, both magnitude and relationship (correlation) between, in your estimates of (a,b).

2.4.2.2 Correlation in Estimates of (a,b)

In Q5 we offered you three options for expressing joint uncertainty in estimating the seismicity parameters (a,b). These were:

- o Estimates of (a,b) are independent
- o Estimates of (a,b) are partially negatively correlated
- o Estimates of (a,b) are perfectly negatively correlated

In reviewing these alternatives, because of the constraints placed on implementing correlation between a,b in the analysis, we do not feel that you were given sufficient options to fully express your state of uncertainty in

estimating these parameters. Thus, we have revised these options for expressing correlation between your estimates of a and b.

<u>Option 1:</u> Estimates of a,b are <u>independent</u>

Estimates for the two parameters a,b are independent if, given any value of a, the most likely value and uncertainty range for b is the same. Thus, your estimate of the most likely value and your state of knowledge (as expressed by your uncertainty bounds) about the slope,b, of the magnitude recurrence model is the same for all values of the intercept, a.

In this case, one need only specify the most likely values $(\hat{a},\hat{b})$ and the uncertainty ranges (a_L,a_U) and (b_L,b_U).

<u>Option 2:</u> Estimates of (a,b) are <u>partially correlated</u>

Estimates of (a,b) are partially correlated if the most likely value and/or uncertainty range of b changes for different values of a throughout the range of values of a. That is, your estimate of the slope and your uncertainty in the estimate vary over the range of estimates of the intercept.

To implement this option, it is necessary for you to specify:

- o most likely value and uncertainty range for a, i.e. $\hat{a}$, (a_L,a_U)
- o three sets of most likely values and uncertainty ranges for b corresponding to $\hat{a}$, a_L, a_U, i.e
  - o for $\hat{a}$: $\hat{b}$, (b_{ML},b_{MU})
  - o for a_L: $\hat{b}_L$, (b_{LL},b_{LU})

- for a_U: $\hat{b}_U$, (b_{UL}, b_{UU})

subject to the restriction $\hat{b}_U \leq \hat{b} \leq \hat{b}_L$

Option 3: Estimates of (a,b) are fully correlated

Estimates of (a,b) are fully correlated if a specific value of b is associated with each value of a throughout its range. In this case, the values of (a,b) go together in unique pairs.

The information needed for this option are:

- most likely value and uncertainty range for a, i.e. $\hat{a}$, (a_L, a_U)

- values of b associated with $\hat{a}$ and the bounds a_L, a_U, i.e.
  - for $\hat{a}$: $\hat{b}$, the most likely value of b
  - for a_L: $\hat{b}_L$
  - for a_U: $\hat{b}_U$

Given your option, the joint uncertainty in estimating (a,b) will be handled in the seismic hazard analyses in the following ways:

Option 1: This is handled as it has been in the past. That is, uncertainty distributions $F(a: \hat{a}, a_L, a_U)$ and $G(b: \hat{b}, b_L, b_U)$ are created based on your inputs. Uncertainty in the hazard due to uncertainty in estimating seismicity, i.e. (a,b), is simulated based on independently selecting values out of each distribution $F(a: \cdot)$, $G(b: \cdot)$ to create a pair of parameters (a,b) for estimating seismic hazard.

Option 2: This option replaces the partial correlation option in Q5. Initially, the uncertainty distribution $F(a: \hat{a}, a_L, a_U)$ is created based on your inputs about a. Given an $\hat{a}$, a_L, $\hat{b}$, $\hat{b}_L$, there is a magnitude m_L such that

$$\hat{a} + \hat{b}m_L = a_L + \hat{b}_L m_L$$

Similarly, there is a magnitude m_U such that

$$\hat{a} + \hat{b}\, m_U = a_U + \hat{b}_U\, m_U$$

For any a* in $(a_L, \hat{a})$, the corresponding most likely value of b, denoted $\hat{b}^*$, is such that

$$a^* + \hat{b}^*\, m_L = \hat{a} + \hat{b}\, m_L$$

and, similarly, for a* in$(\hat{a}, a_U)$ the most likely value $\hat{b}^*$ is such that

$$a^* + \hat{b}^*\, m_U = \hat{a} + \hat{b}\, m_U$$

If $\hat{b}_L = \hat{b}$ and/or $\hat{b}_U = \hat{b}$, then the appropriate $\hat{b}^* = \hat{b}$ for all a*.

The uncertainty range by b, given any a*, is based on a linear interpolation of the bounds at $\hat{b}$ and at either b_L or b_U, if a* is in$(a_L, \hat{a})$ or $(\hat{a}, a_U)$ respectively. The most likely value $\hat{b}^*$ and bounds (b^*_L, b^*_U) are used to create the conditional uncertainty distribution of b, given a^*, i.e. $G(b \mid a^*: \hat{b}^*, b^*_L, b^*_U)$.. A value b^* is selected from this distribution and combined with a^* to predict the seismic hazard.

<u>Option 3:</u> In this case a unique b is associated with each value of a. The procedure for identifying a b^* for any a^* in the range of a is the same as that for evaluating the most likely value b* in Option 2. In this case, there is no uncertainty associated with b*.

A graphical view of how these options are implemented is given in Fig. 4 a,b,c where we have only shown the most likely value $\hat{a}$ and upper limit a_U for simplicity. We believe that these three options will give you a range of possibilities of expressing joint uncertainty in estimating the seismicity parameters.

3. QUESTIONS

Included with this questionnaire are

- o Estimates of seismicity, in terms of the parameters (a,b), for each of the source zones you have identified in response to the questionnaires on zonation. If only a few earthquakes have occurred within a zone, the historical data may be insufficient to estimate seismicity. In that case, estimates of (a,b) are not included for that zone.

- o A summary of your inputs on seismicity for your previously identified zones (i.e, zones identified prior to your response to Q7)

This information has been provided for your reference, review and use in responding to this questionnaire. Combining this information with other sources of information about EUS seismicity you have at your disposal, please respond to the following questions about the seismicity associated with each of the source zones you identified in response to Q7.

For each zone, please fill in Table 2 by providing

- o The zone index (**column 1**) based on the index numbers identifying the zones on your maps of the zonation of the EUS.

QUESTION 3.1 The magnitude scale (**column 2**) you are using in responding to the questions about seismicity.

- o If you use the M_{bLg} scale only, skip to Question 3.2.
- o To transform between the MMI and M_{bLg} scales when using the different ground motion models, we will use the relation

$$(MMI)_E = 2\ M_{bLg} - 3.5$$

If you do not feel that this is the best model for relating the two scales, please indicate the values you want to use in the appropriate place in Table 3.

- If you use any other magnitude scales, please provide the models for relating each of the scales to the M_{bLg} scale; do so in the appropriate place in Table 3.

QUESTION 3.2 The saturation value (**column 3**) of the magnitude scale if you are constrained by magnitude scale saturation in your response to any questions about seismicity.

QUESTION 3.3 Estimates of the upper magnitude cutoff, M_U, i.e, the highest magnitude supportable by the geological and physical conditions within the zone, in terms of

- The most likely value (or best estimate), $\hat{M}_U$ (**column 4**)
- Uncertainty bounds, M_{UL}, M_{UU}, **(column 5)** which, with 95% confidence, envelope the true value of the highest magnitude supportable within the zone.

QUESTION 3.4 The magnitude range, M_{LB}, M_{UB}, **(column 6)** for which the linear model, $\log N_m = a + bm$, for the magnitude-recurrence relation is applicable. Since everyone has chosen the linear model in the past, this and the remaining questions on seismicity are written relative to that model. If you feel the linear model is inadequate, please indicate, at the appropriate entry in Table 3, and make the necessary adjustments in your responses to the questions on seismicity to completely specify the model for seismicity for each zone.

- o If $M_{LB} = M_0 = \begin{matrix} 3.75 \text{ in } M_{bLg} \\ IV \text{ in } MMI \end{matrix}$, skip to Question 3.5

  and do not respond in **columns 7-9**

- o If $M_0 < M_{LB}$, please estimate the occurrence rate, λ_0, of earthquakes of magnitude M_0 or greater by providing

  - The most likely value, $\hat{\lambda}_0$, **(column 7)**
  - Uncertainty (95% confidence) bounds, λ_{0L}, λ_{0U}, **(column 8)**
  - The time length, if other than per year, **(column 9)** corresponding to your estimates.

QUESTION 3.5 Your choice **(column 10)** of methods for adjusting the linear magnitude-recurrence model for $M_{UB} < m < M_U$ to satisfy the restriction that $N_{M_U} = 0$. The alternatives

- o LLNL model (code LL)
- o Truncated Exponential model (code TE)

have been discussed in section 2.3.

QUESTION 3.6 Estimates of the parameters (a,b) of the linear magnitude recurrence model, in terms of

- o The time length, **(column 11)** if other than per year, corresponding to the estimates of (a,b)
- o The most likely value of the intercept a, $\hat{a}$, **(column 12)**
- o Uncertainty (95% confidence) bounds for a,

(a_L, a_U), **(column 13)**

- The model (**column 14**) for your joint uncertainty (or confidence) in the estimates of the intercept, a, and slope, b, of the magnitude-recurrence model. The alternatives
  - Independent (code I)
  - Partially correlated (code P)
  - Fully correlated (code F)

  have been discussed in section 2.4.2.2
- Estimates of the slope b (**column 15**),
  - If (a,b) independent,
    - most likely value of b, $\hat{b}$ (**column 15-1**)
    - uncertainty bounds for b, (b_L, b_U) **(column 15-2,3)** which are applicable for all values of a
  - If (a,b) partially correlated, most likely value and uncertainty bounds, given $\hat{a}$, a_L, a_U, i.e, values
    - $\hat{b}$, (b_{ML}, b_{MU}) **(column 15-1,2,3)**
    - $\hat{b}_L$, (b_{LL}, b_{LU}) **(column 15-1,2,3)**
    - $\hat{b}_U$, (b_{UL}, b_{UU}) **(column 15-1,2,3)**

    such that $\hat{b}_U \leq \hat{b} \leq \hat{b}_L$
  - If (a,b) fully correlated, most likely value, given $\hat{a}$, a_L, a_U, i.e. values $\hat{b}$, $\hat{b}_L$, $\hat{b}_U$ **(column 15-1,2,3)**

TABLE 1

Estimates of the Expected Number of Earthquakes Based on a Linear Model with a = 3.59, b = -0.9, M_{LB} = 3.75, M_{UB} = 7.5

	LLNL Model		Truncated Exponential Model	
M	N_m	$N_{\Delta m}$	N_m	$N_{\Delta m}$
3.75	1.64059		1.64059	
4.00	.97724	.66335	.97696	.66363
4.25	.58210	.39514	.51866	.39530
4.50	.34674	.23536	.34619	.23547
4.75	.20654	.14020	.20594	.14025
5.00	.12303	.08351	.12239	.08355
5.25	.07328	.04975	.07262	.04977
5.50	.04365	.02963	.04298	.02964
5.75	.02600	.01763	.02532	.01766
6.00	.01549	.01051	.01480	.01052
6.25	.00923	.00626	.00854	.00626
6.50	.00550	.00373	.00481	.00373
6.75	.00327	.00223	.00258	.00223
7.00	.00195	.00132	.00126	.00132
7.25	.00116	.00079	.00047	.00079
7.50	.00069	.00047		.00047
7.75		.00069		

TABLE 2

Zone Number	Magnitude Scale	Saturation Value	UPPER MAGNITUDE CUTOFF, M_U			MAGNITUDE-RECURRENCE MODEL				
			M_U	(Col. 5)		Linear Range (Col. 6)		Occurrence Rate λ_0	(Col. 8)	
(Col. 1)	(Col. 2)	(Col. 3)	(Col. 4)	M_{UL}	M_{UU}	M_{LB}	M_{UB}	(Col. 7)	λ_{oL}	λ_{oU}

MAGNITUDE-RECURRENCE MODEL									
Time Length	Model Adjust	Time Length	Intercept, a			slope, b			
			a	(Col. 13)		(Col. 14)	(Col. 15)		
(Col. 9)	(Col. 10) (LL or TE)	(Col. 11)	(Col. 12)	a_L	a_u	Corr. (I,P,F)	1 b	2 b_L	3 b_U

(1) Please use the index numbers identifying the zones on your maps of the zonation of the EUS

TABLE 3

Respond to these questions <u>ONLY</u> if appropriate.

QUESTION 3.7.1

a. $(MMI)_E = \_\_\_\_\_ \; M_{bLg} + \_\_\_\_\_ \, .$

b. Models for relationships between M_{bLg} and magnitude scale you are using in your response

- o Magnitude scale : _____
- o Model

$$\_\_\_\_\_ = \_\_\_\_\_ \; M_{bLg} + \_\_\_\_\_ \, .$$

QUESTION 3.7.2 Uncertainty distribution for M_u (only if triangular distribution is inappropriate)

QUESTION 3.7.3 Magnitude recurrence model if linear model is inappropriate

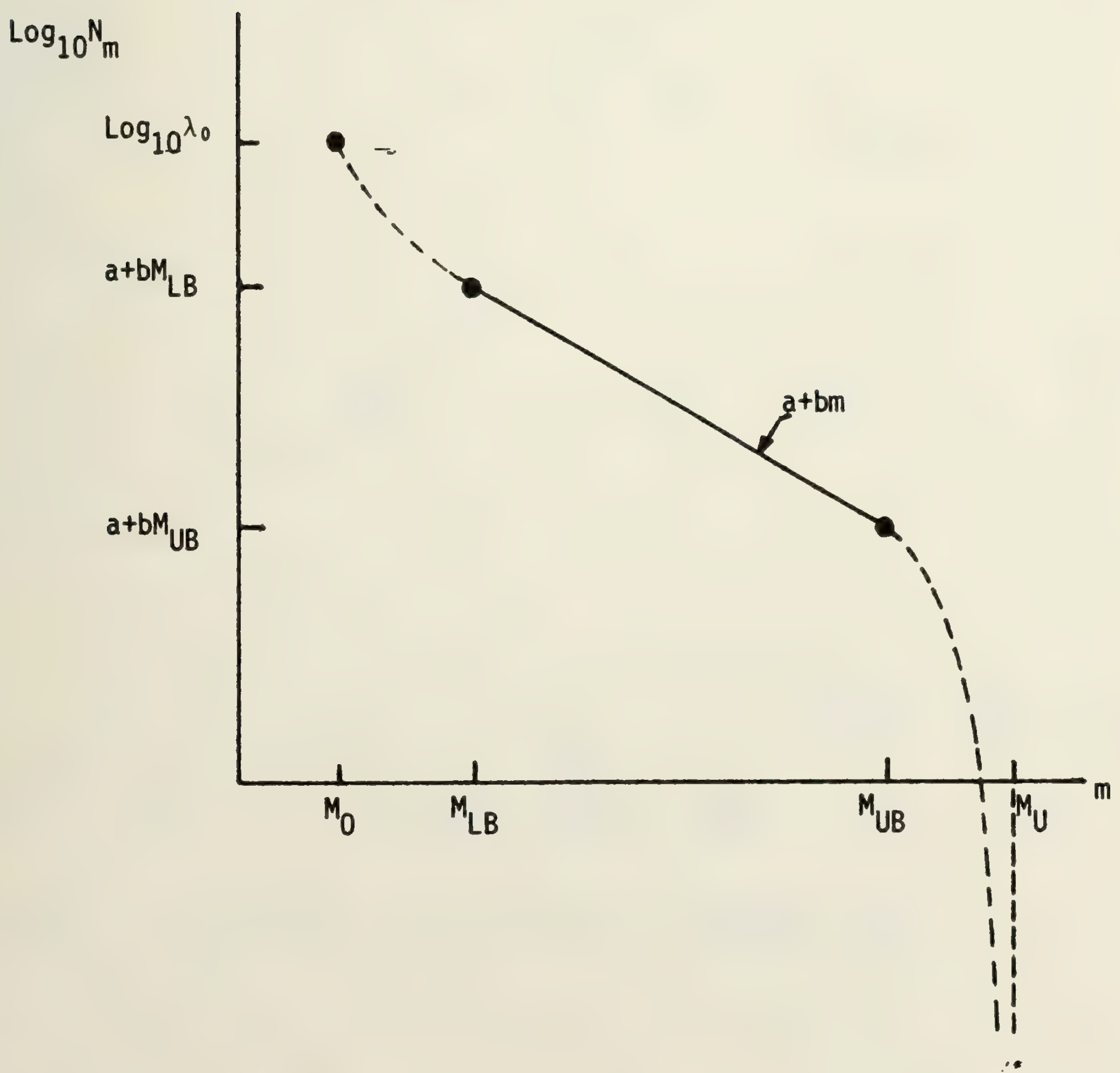


Figure 1. LLNL Adjusted Magnitude-Recurrence Model.

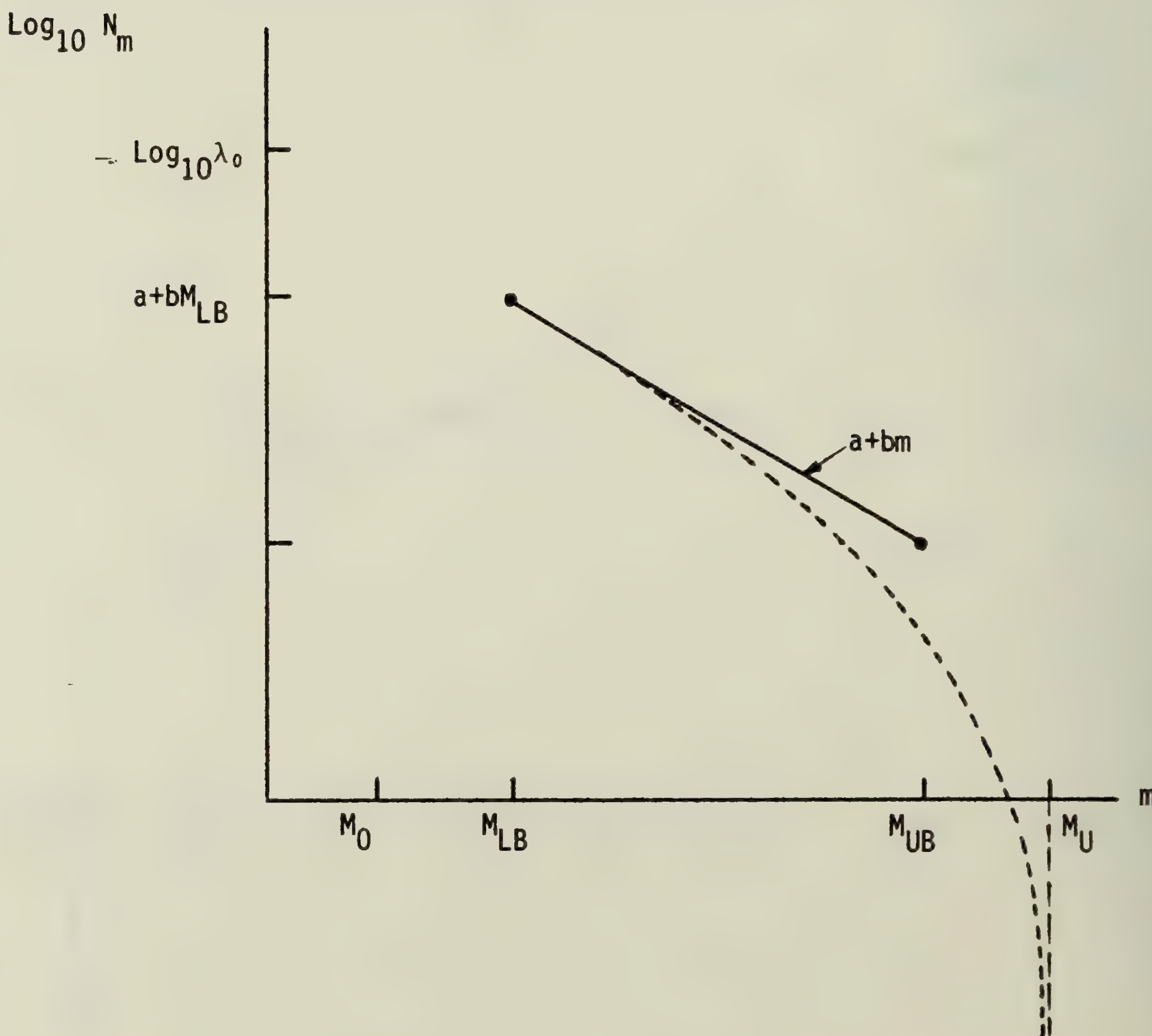


Figure 2. Truncated Exponential Adjusted Magnitude-Reccurence Model.

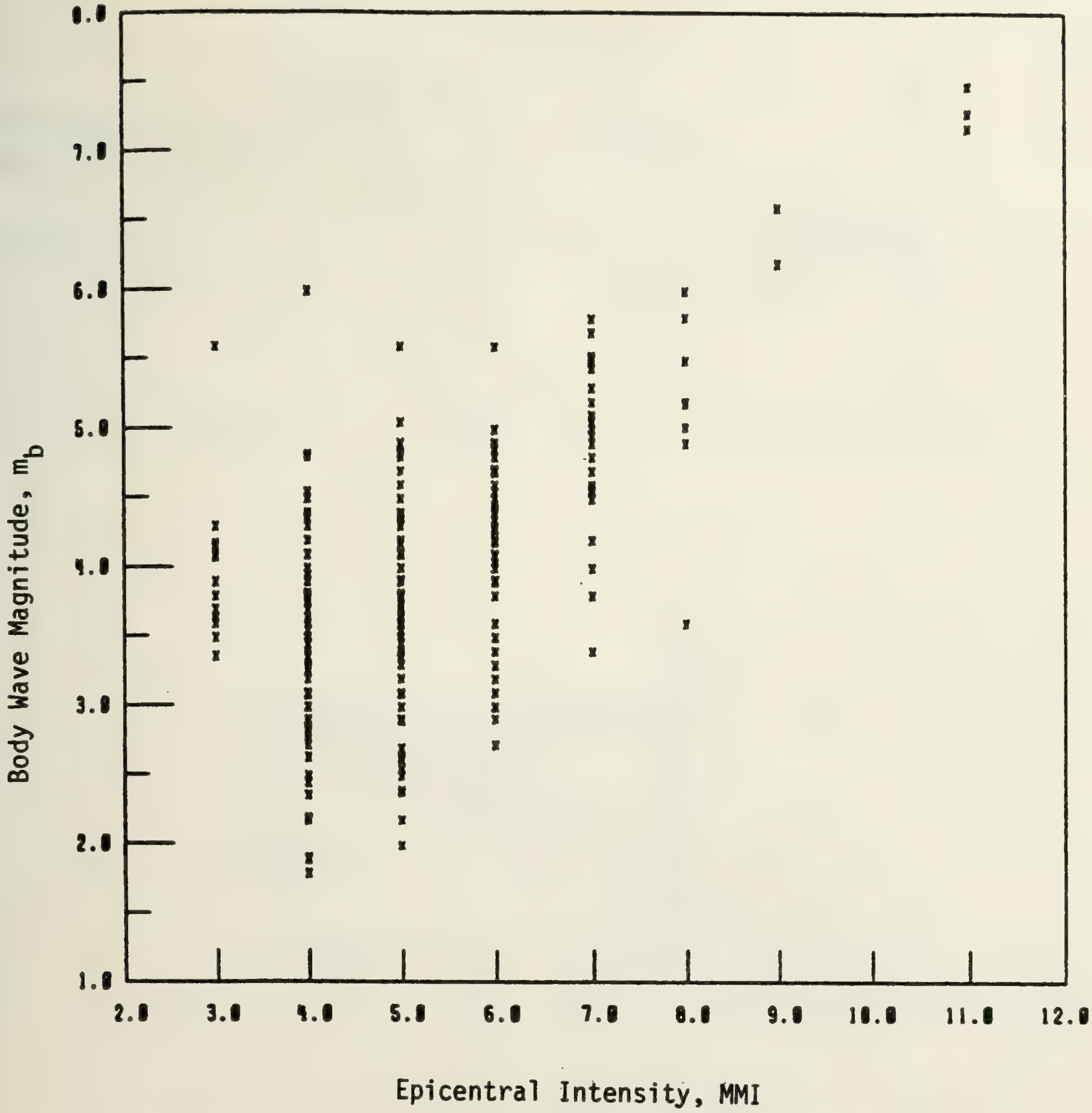


Figure 3. Magnitude, m_b, Versus Epicentral Intensity, MMI

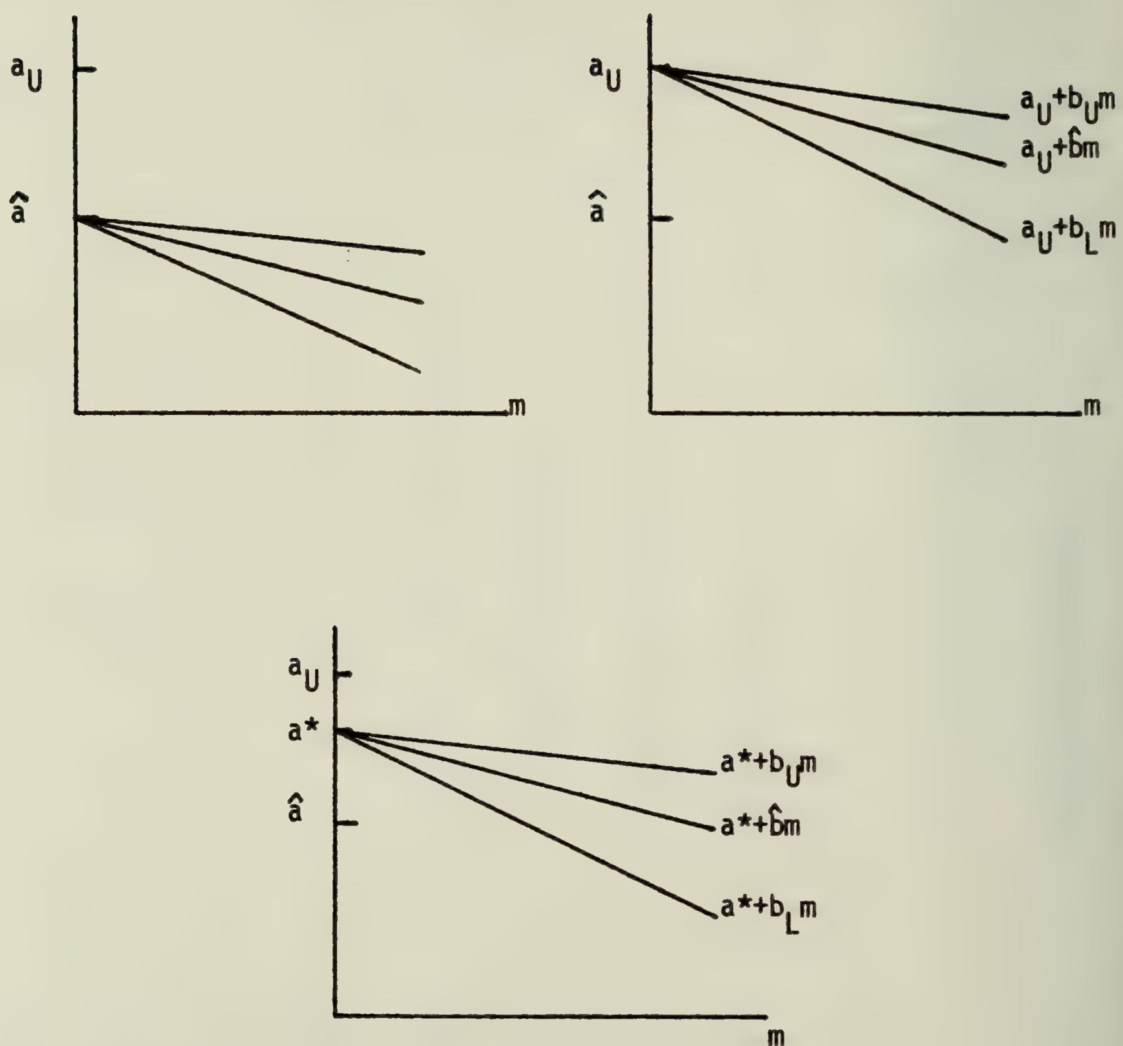


Figure 4.a (a,b) Independent- most likely value and range of b is the same for all a values

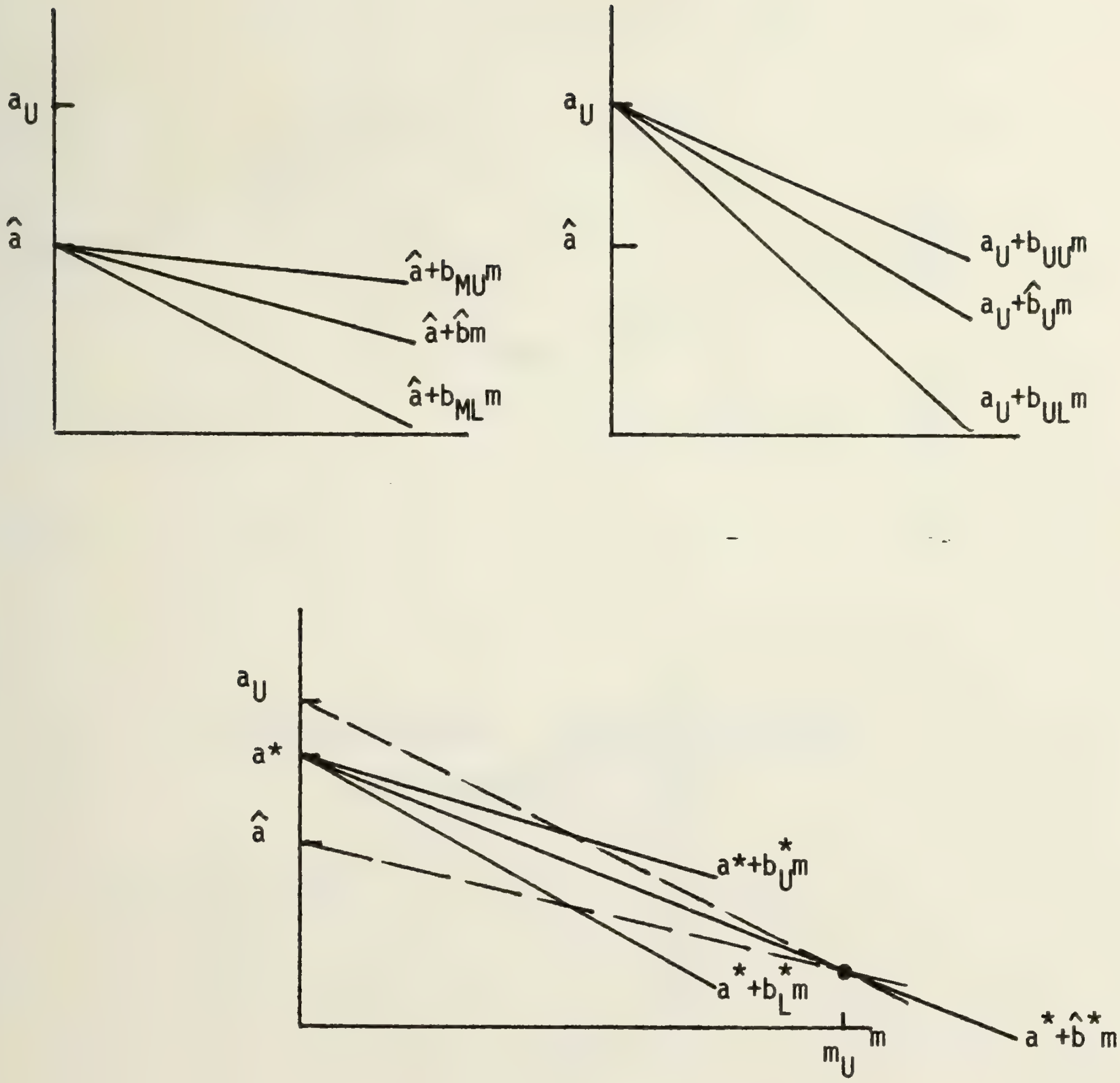


Figure 4.b (a,b) Partially correlated- most likely value and/or range of b vary with different a values

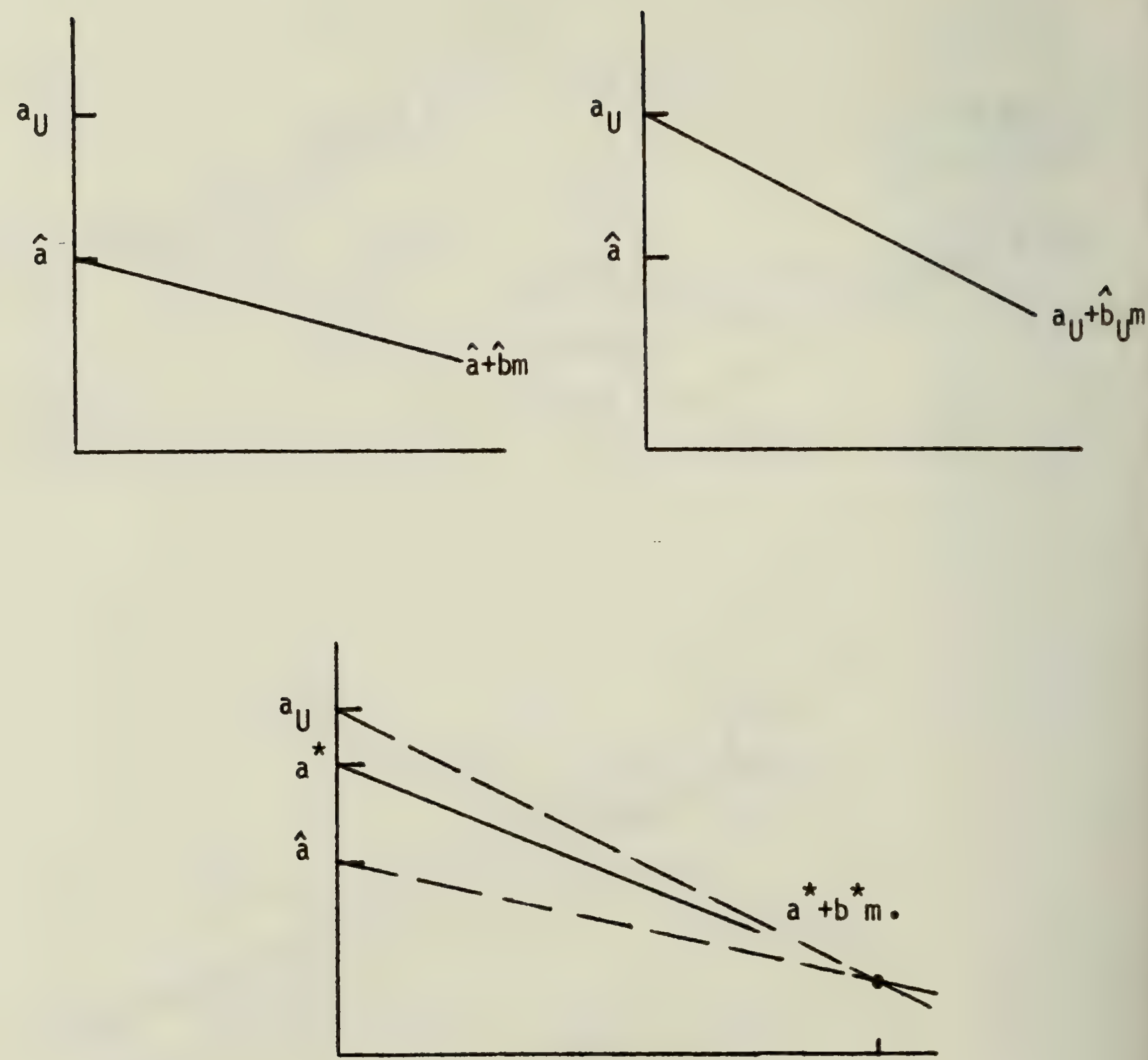


Figure 4.c (a,b) Fully correlated-unique b* is associated with each a*

TENTH QUESTIONNAIRE - GROUND MOTION FEEDBACK

QUESTIONNAIRE II (Q10)

TENTH QUESTIONNAIRE - GROUND MOTION FEEDBACK

QUESTIONNAIRE II (Q10)

1. INTRODUCTION

There are several reasons for having an additional feedback loop with our Ground Motion (GM) Panel members. In particular:

- o Considerable progress has been made in the development of the Random Vibration model.

- o EPRI has funded a number of studies to address specific issues.

- o To allow us to expand our panel.

At our two-day GM workshop we attempted to review in some detail the work that EPRI has funded and to examine the basic assumptions of the Random Vibration model.

The purpose of this document is: (1) to briefly summarize the points that were discussed at our meeting and which we think are important for you to consider in making your selections and, (2) to ask you the question which will give us your selections.

These elements are generally covered in Sections 1-5. The last section contains the questions.

It should be kept in mind that in the end we are asking you to select

- o GM models for peak ground acceleration (PGA)
- o GM models for peak ground velocity (PGV)
- o GM models for the 5% damped relative velocity spectrum (S_V)

For simplicity much of our discussion will be centered in the GM models for PGA, however, we are equally interested in PGV and S_V.

2. LIMITATIONS IMPOSED BY LLNL COMPUTER PROGRAMS/APPROACH

2.1 Earthquake Size Measures

At our workshop there was some discussion about the particular magnitude definition being used with considerable emphasis being put on which formula, wave type, etc. should be used. Given this background it is important to keep in mind that no very precise definition of magnitude is being used in our study. True, we implied to our Seismicity Experts (S-Experts) that we wanted to work in terms of m_{bLg} and/or epicentral intensity I_0. However, we did not give the S-Experts a precise definition of what we meant by m_{bLg}, primarily because it would have been totally meaningless. The S-Experts have to rely on the various regional catalogs. These catalogs are not consistent, and in them, for much of the time covered by the catalog the only measure of earthquake size is I_0. The S-Expert has to convert I_0 in some manner to a magnitude measure if he chooses to give his seismicity model in terms of magnitude. It is worthwhile to note that only two S-Experts chose to work in terms of intensity, the other nine chose to do a conversion to magnitude. The net effect of this is that the magnitude measures being used by nine of our S-Experts are somewhat uncertain. Effectively

$$m_{Lg} = m_{Lg} = m_b = m_N$$

for this study. This may be an uncertainty that you need to factor into your thinking.

It is also important to keep in mind that two of the S-Experts have provided their earthquake recurrence models in terms of I_0. These two S-Experts provided a relation to convert I_0 to magnitude at the time the probability

$$P(GM>gm|I_0,R)$$

is computed in our program for use in GM models that are in terms of magnitude. You should note that you can provide different weights or GM models for this case.

2.2 Distance Metric

The distance metric in our program is the epicentral distance. If you want to assign some average depth to the earthquakes then a depth parameter should be supplied if one is not already contained in a given ground motion model.

At our workshop it was pointed out that in some cases the use of a epicentral distance metric leads to an under estimation of the hazard at a site. However, this point is at best very "fuzzy" because no one has carefully examined the question using a GM model based on closest approach (with fault rupture included in the hazard analyses) and a GM model based on epicentral distance when both GM models were developed consistently from the same data set. In this case it is not at all clear that the closest approach analysis would lead to a higher seismic hazard for the case when the faults cannot be defined and hence a random direction for rupture must be assumed.

On the other hand it is not clear what the distance metric actually represents in the various Eastern North American (ENA) GM models . For earthquakes of $m<6$ it may not be a very significant uncertainty. However, for very large earthquakes the metric question certainly contributes to the overall uncertainty.

2.3 What is Modeled

In our analysis no attempt is made to model source-site geometry effect, nor account for a particular travel path. However, the GM models often include a term for regional values of Q and the models/weights selected can vary by region. Figure 2.1 shows roughly the four regions allowed in our analysis. This choice of regions is fixed. Also, as discussed in Section 5, We do include a correction to account for local site soil conditions.

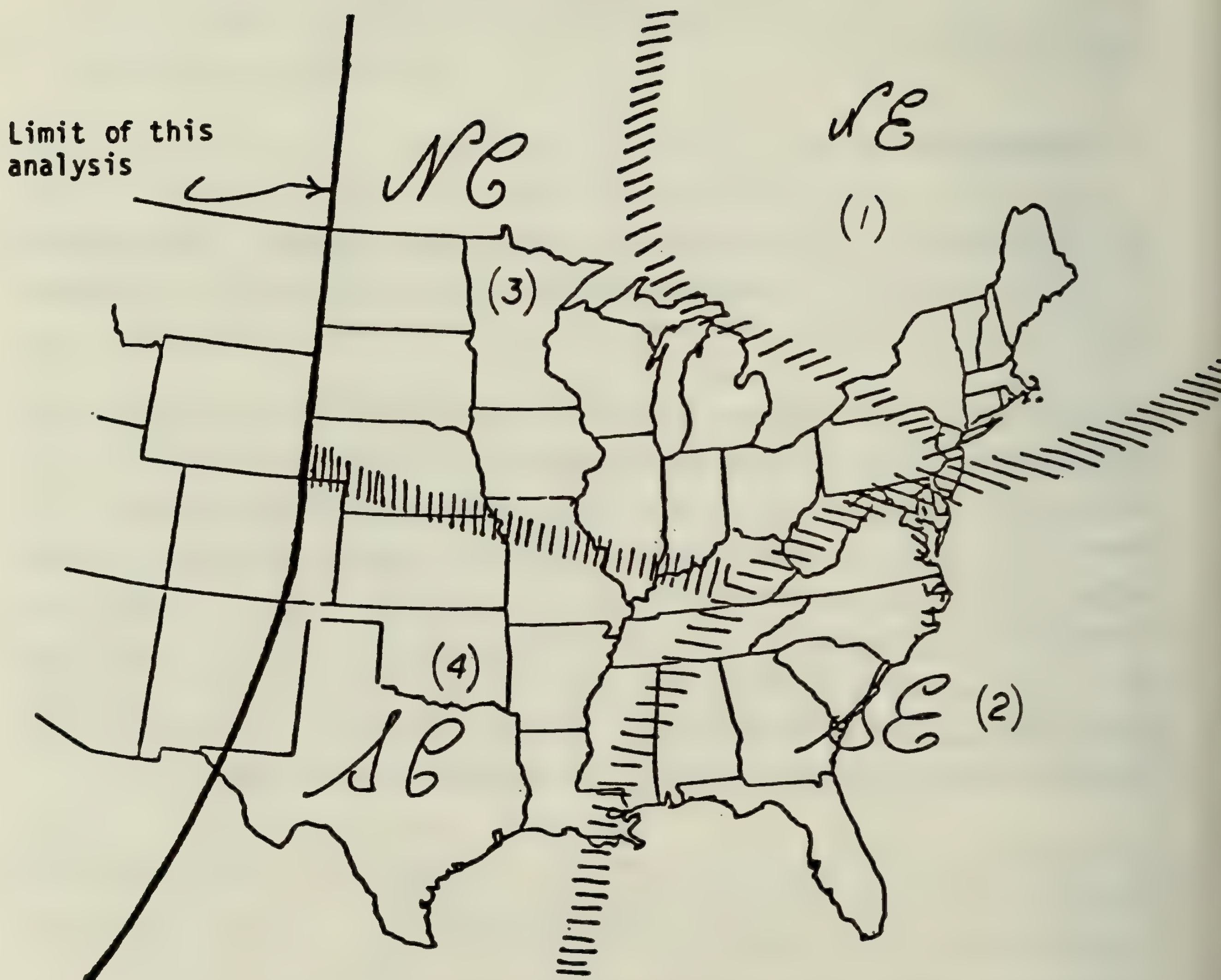


Fig. 2.1 Identification of four regions of the Eastern U.S. based on a compilation of the seismic zonation expert maps developed in this study and a map of Q_0-contours from Singh & Herrmann (1983).

3. MODELING UNCERTAINTY

The hazard analysis methodology, as developed for the EUS Seismic Characterization Project, involves the probabilistic modeling of earthquake occurrence and magnitude distribution throughout the EUS. In addition, the ground motion at a nuclear power plant, described in terms of PGA, PGV and spectral velocities, due to earthquakes in the vicinity of the plant is considered to be a random process, as well, due to the variations in the geologic environment of the earthquake source, the plant site and the travel path of the ground motion from the source to the site. Thus, the underlying view in developing the hazard analysis is that the physical processes involved in earthquake occurrences and the subsequent magnitude of the earthquakes and the resultant ground motion at any site are random (or variable) processes.

The methodology for assessing the hazard and the final description of the hazard is probabilistic. The hazard analysis involves developing probability models which describe the random nature of the seismic hazard process. It is recognized, in proceeding through the analysis, that such models can only be approximations to reality. Therefore, the hazard curves, developed through the probabilistic modeling, are only estimates of the actual hazard. Since the hazard analysis is an estimation process, it has certain uncertainties associated with it, e.g., the uncertainty of using mathematical models or of using limited historical earthquakes recordings as a basis for developing ground motion models for describing the expected or average ground motion at a site as a function of the earthquake magnitude and distance of the site from the source. Such uncertainties have generally been referred to as "modeling uncertainties". It is important that modeling uncertainties be recognized and the level of modeling uncertainty associated with the hazard analysis be quantified. The LLNL hazard analysis methodology attempts to account for modeling uncertainty throughout all phases of the analysis. Thus, modeling uncertainty is associated with the characteristics of zones, seismicity as well as ground motion modeling. These uncertainties are combined and propagated through the analyses and finally associated with the hazard estimate by producing quantile estimate of the hazard in addition to a single point (i.e. single hazard curve) estimate.

Another consequence of modeling earthquake occurrence, magnitudes and ground motion attenuation as random processes is that it is important at all stages of the analysis to distinguish between the random variation being modeled and the uncertainty associated with modeling the random variation. The former, random variation, is assumed inherent in the physical processes being modeled, e.g. the basic view is that earthquake occur, over time, as a random or unpredictable process. This process can be described, approximately, by some probabilistic model. For example, in this project the occurrence of earthquakes is modeled as a stationary (over time) Poisson process, i.e., earthquake occur "at random" at a rate which is consistent over time. Similarly, the ground motion at a site is assumed to be a random variable due to variations in the geologic environments affecting the ground motion. Thus, due to the unpredictability of the earthquake location and the fluctuations in the environment through which the ground motion propagates, the motion at a site is random. Except for two ground motion models (see section 4) the random variation in ground motion, given an earthquake magnitude and distance, is modeled, approximately, by a lognormal distribution.

Modeling uncertainty, on the other hand, is not associated with the physical world, although it could be a consequence of the random variation of random processes, e.g. the uncertainty associated with using a random sample to estimate the expected value of a random variable. Specifically, modeling uncertainty is a measure of how well the models used in the hazard analysis describe the physical world. If the model is "known" to describe the world (i.e. random process) very well, modeling uncertainty would be low. Conversely, if the model and its parameter values are based on very limited information (in terms of historical data and/or other sources of information) then the modeling uncertainty should be larger. If the choice of model and its parameter values is based on data alone then the uncertainty may be attributed to the "random" nature of the available (sample of) data. On the other hand, if the choice of models and parameter values are based on personal (subjective) opinions, then the modeling uncertainty is an expression of the individual's confidence (or lack of confidence) in the information used to develop and express their opinions.

With respect to ground motion modeling and your participation on the Ground Motion Panel, two issues regarding uncertainties should be emphasized. One, how is modeling uncertainty introduced into the ground motion modeling phase of the hazard analysis? There are several ways that the uncertainties associated with developing GM models could be handled, e.g. one might ask for a single GM model plus some band about the curve which one is confident encompasses the expected value of GM given an earthquake magnitude, m, and distance, R. (See Fig. 3.1)

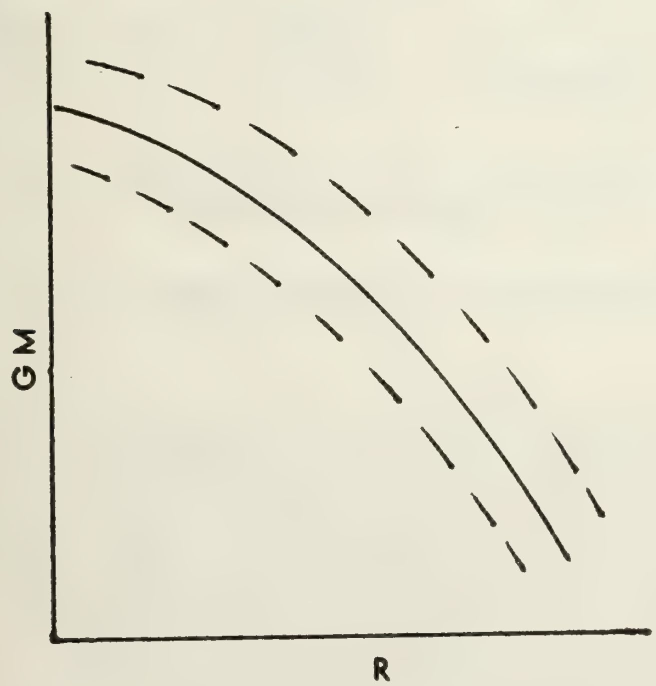


Fig. 3.1 Single GM Model Plus Confidence Bands

For the LLNL project, modeling uncertainty for GM models is handled by asking you to select, potentially, several GM models which in effect, cover a range of values of the expected GM, given m, R as shown in Fig. 3.2

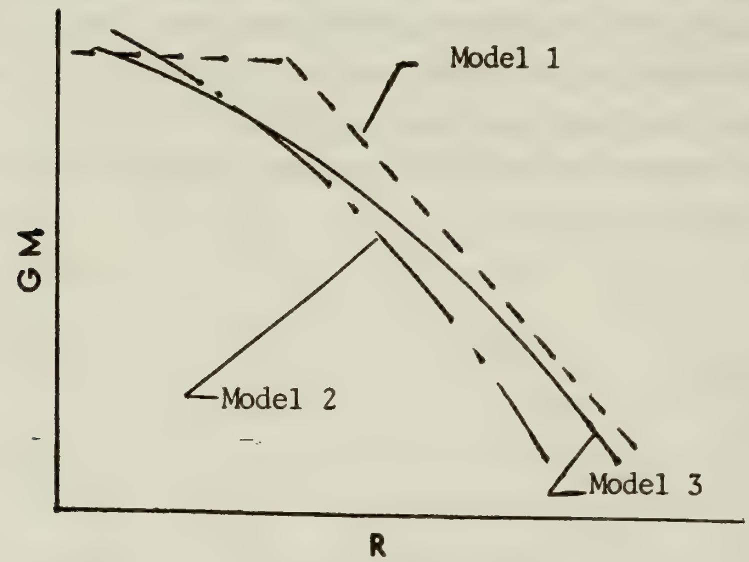


Fig. 3.2 Several GM Models Resulting in a Range of Expected Log GM Values

This range should reflect your confidence in the expected GM being predicted, given m, R. We further ask you to weight, i.e. assign relative weights, to each of the models. This, in effect, associates a distribution to the expected GM, given m, R where the weights are a reflection of your (relative) confidence or likelihood that the expected GM is at the level (or approximately at the level) produced by the given model. Thus, if you are "confident" that the expected GM is within a small range you should select models which produce similar results whereas if you are uncertain about the level of GM, as a function of m, R, that could be expected then you should choose a group of models which produce a more substantial range of values for the expected GM.

A second issue regarding uncertainty that you should be sensitive to in your thinking about GM modeling is the separation of random variation and modeling uncertainty. This arises when you are asked to estimate the random variation (in terms of ln GM) associated with the GM's for a fixed magnitude and

distance. This is discussed again in Section 6, however it is an important enough issue to mention it here also. In asking you to estimate the standard deviation of the ln GM, given m, R, we would like to have your opinion of what the inherent random variation in M can be expected, given m, R. This is an estimate of the GM variation due to the physical variations in the environments affecting ground motion. In estimating this standard deviation, it should be recognized that when using historical data to develop GM models, the residuals about the model are due partially to the inadequacy of the model as well as random variation. Thus, the modeling uncertainties (inadequacies) of the models should be deleted prior to estimating random variation. If this is not done then the uncertainty in modeling the expected GM:

- o Is introduced twice-once through the selection of several models and also as a component of random variation.

- o Falsely inflates the random variation in GM, given in, R.

Can the modeling uncertainty in GM models be separated from random variation? There does not seem to be an obvious way of doing this. Most GM models are based on fitting models to historical data, either as a bases for developing the model and estimating the values of the model coefficients or for "verifying" that a model "fit the physical world". In either case the data is scatter about the fitted model. It is tempting to attribute all of the variation to random variation. However, some of the variation is likely to be due to the model being only an approximation to the real relationship between GM and earthquake magnitude and distance. One way, perhaps, of separating random variation from modeling uncertainty is to look at the scatter about a model at a m,R value which you feel the model estimates the expected GM exceptional well. One might also consider the variation in the expected GM for several models in comparison to the total variation about a model. This might suggest the extent to which model uncertainty contributes to the total scatter in the data. Also, as is discussed in Section 6, you might want to consider to what extent the correction for "local site effects" requires an adjustment in your estimate of the random variation in GM.

4. REVIEW OF AVAILABLE MODELS

4.1 Empirical Models

4.1.1 Direct Regression Models

This approach for deriving a GM model is ideally suited to our project. In the application of this approach at least three issues arise:

1. The adequacy of the data, i.e., given the variability between earthquakes, is there sufficient data to reliably estimate the parameters of the model?

2. Questions about which data should be included: i.e., generally we do not know local site conditions.

3. Uncertainty about the proper functional relation for the proposed model.

For ENA the first issue is dominant as the ENA data base consists of only four small sets of data:

1. "Strong" ground motion data recorded from only four ENA Earthquakes in the $4 \leq m_b \leq 5$ range within 50 km of the epicenter. Of this data, much of it was recorded at sites where we would expect to see significant local site effects. Data from a few earthquakes with $m_b < 3$ also exists.

2. Data recorded on standard accelerographs at distances greater than 50 km. This data set is made up of data from five earthquakes in the magnitude range of 4 to 5.3. Only one of these earthquakes, the New Hampshire earthquake, was also recorded in the "near" source region.

3. ECTN data. The ECTN stations record only the vertical velocity data between 0.5 to 20 Hz. Data is available from six earthquakes. The largest magnitude is 5.6. Generally, the distances are greater then 100km.

4. LRSM data. LRSM stations record three components of motion over the frequency range of 0.5 to 7 Hz. The distances are generally greater than 100 km. The magnitude range is 3 to 4.8.

Although the first issue is dominate for ENA, the second issue is also important because several of the stations in the sparse strong motion data set were recorded at very shallow soil sites or at dams. With regard to the third issue only one relatively standard functional form of the model was discussed at our November 5 and 6 meeting by Veneziano. Other forms are possible, but it is evident that the data set is too sparse to allow any resolution between competing models. Specifically, Veneziano used a model of the form

$$\mathrm{Ln}\,(Y) = b_0 + b_1 m_b + b_2\,\mathrm{Ln}(R) + b_3 R + b_4 V + b_5 S + B + E \qquad (4.1.1)$$

where

- Y = GM parameter, e.g., PGA
- R = hypocentral distance
- V = 1 for vertical component
  0 for horizontal component
- S = 1 soil site
  0 rock site
- B = variation between earthquakes
- E = variation between data for a given earthquake
- b_i = constants estimated from the data

Both B and E were assumed to be normally distributed with a zero mean. Veneziano used a weighted regression analysis to determine the parameters , b_i, of the model. Veneziano used the ENA data set and added the Gazli, USSR data

point. He gave weights of 0.2 to the vertical-component data and data from the Gazli earthquake. See Risk Eng. (1986), Section 4 for details.

As noted, Eq. (4.1.1) is a standard form for the GM model. However, Campbell (1981) has suggested a different functional form which he believes better models the scaling of the GM with magnitude and the near source attenuation of GM for large earthquakes. Campbell's model is of the form

$$\mathrm{Ln}(Y) = b_1 + b_2\, m_b + b_3\, \mathrm{Ln}(R + C(m_b)) + b_4\, R \tag{4.1.2}$$

$$\text{where } C(m_b) = C_1 \exp\,(C_2 m_b)$$

Clearly, there is not adequate data to estimate the parameters b_i and C_i in Eq. (4.1.2).

Table 4.1.1 gives the coefficients of Eq. (4.1.1) as determined by Veneziano. Comparisons of this model to other models are made in Section 4.4. For future reference it is interesting to note the values of the coefficient of the m_b and V terms (b_1 and b_4) in Eq. (4.1.1).

TABLE 4.1.1

Veneziano's Fit of Eq. 4.1.1 to the ENA Data Set

GM Parameter	b_0	b_1	b_2	b_3	b_4	b_5
Acceleration	1.98	1.24	-1.18	-0.003	-1.17	0.33
$S_v(10)$	-2.85	1.27	-0.89	-0.003	-1.12	0.42
$S_v(1.)$	-8.51	2.22	-0.84	-0.003	-1.01	0.87

The b_1 coefficient controls how the GM scales with magnitude and the b_4 coefficient gives the relation between the horizontal and vertical components. If one accepts the argument by Herrmann and Nuttli (1982) that M_L

in the WUS is equivalent to m_b in ENA, then Veneziano's results suggests that for ENA earthquakes the GM scales differently than in the WUS. For example, Joyner and Boore (1981) found that Ln (PGA) scales as 0.57 M_L compared to 1.2 m_b found by Veneziano. We will return to this point later.

The coefficient b_4 gives the relation between the horizontal and vertical components. Veneziano's results suggest that Z/H = 0.3 or the vertical component is about a factor of three smaller than the horizontal component on the average.

4.1.2 Intensity Based Models

Because there is so little ENA strong GM data (and much of it is very recent) a number of GM models have been developed using intensity data. Typically one obtains a relation of the form

$$I_s = F(I_0, R) \tag{4.1.3}$$

where I_s = site intensity
I_0 = epicentral intensity
R = epicentral distance

based on ENA attenuation of intensity. Ideally, one would like to have a relation of the form

$$GM = G(I_s, I_0, R) \tag{4.1.4}$$

based on ENA data. Then Eq. (4.1.3) could be substituted into Eq. (4.1.4) to get GM as a function of I_0 and R. However, there is not sufficient ENA data to obtain the relation (4.1.4.) In the past, relations of the form

$$\begin{aligned} GM &= G_1\ (I_s) && \text{(a)} \\ GM &= G_2\ (I_s,\ M) && \text{(b)} \qquad (4.1.5) \\ GM &= G_3\ (I_s,\ R) && \text{(c)} \\ GM &= G_4\ (I_s,\ M,R) && \text{(d)} \end{aligned}$$

where M = earthquake magnitude/size measure have been developed based on WUS data to overcome this problem. This was discussed at length in our second questionniare on ground motion which is in Appendic C of our report Bernreuter and et. at, 1985. Thus various GM models can be developed by substitution of the relation (4.1.3) into one of the relations (4.1.5) and, if needed, a relation between I_0 and M. Several problems arise with such an approach. First, as discussed by Veneziano at our meeting, if we initially ignore the difficulties of intermixing ENA and WUS GM relations, the only "correct" substitution is to use Eq. (4.1.5d). Correct here is in the sense that the resultant relation represents a consistent regression model. One problem with using Eq. (4.1.5d) is that there are known differences in attenuation between ENA and WUS. For example, in general, for the same M and R in ENA I_s is generally larger than in the WUS. In addition, there may be source differences so that the level and/or frequency content of ENA GM is different than WUS GM. Forms 4.1.5a and b were developed to get around the difference in attenuation between the two regions. In addition, if forms 4.1.5b and d are used one also needs to relate the magnitude measure used for the WUS data to the magnitude measure and/or the epicentral intensity of ENA earthquakes. Finally, one can argue that both relations (4.1.3) and (4.1.5) ignore the fact that intensity is not a continuous variable but only takes on discrete values.

Given all of these defects, why attempt to use intensity? There are at least two reasons. Firstly, we have intensity data from large ENA earthquakes, but no strong GM data. Thus we could hope that the approaches discussed above might shed light on how to scale GM from small ENA earthquakes to large ENA earthquakes. Secondly, most of the historic catalog is in terms of intensity. Thus, Trifunac (and others) argue that it is better to develop both the recurrence models and GM models in terms of intensity then to

introduce additional uncertainties associated with translating both the catalog and WUS magnitudes. Trifunac also suggested that one should not use a functional form like (4.1.3) but one should account for the fact that intensity only takes on discrete values so that a continuous model such as Eq. (4.1.3) is not appropriate.

Before discussing the alternative suggested by Trifunac let us return to the class of GM models obtained by combining Eq. (4.1.3) with one of the relations (4.1.5). There are two ways to proceed. First, one can employ an approach such as the innovative approach Veneziano developed and discussed at our meeting (see also Section 4 of Risk Eng (1986)) and second, combine the regression models from ENA and WUS by assigning a prior distribution for the differences between the vector of coefficients for the known WUS regression relation and the unknown ENA relation. The details are much too complex to go into here, but they are given in Risk Eng. (1986).

It should be noted that although the model Veneziano discussed at the workshop is conceptually the same as discussed in Section 4 of Risk Eng. (1986) some of the details differ. In particular in place of the relation of the form (4.1.5.d) for PGA derived in Section 4 of Risk Eng. (1986) Table (4-8) Veneziano substituted the Murphy and O'Brien (1977) relation of the same form. Veneziano has further modified his results based on consideration of local site effects. See Appendices 1&2, also Section 5.

The coefficents of Veneziano's model are given in Appendix 2 and in Section 6. Of interest here is to note that Veneziano found that Ln(PGA) scales as 1.14 M_{Lg}. The intensity data does not shed any light on the horizontal to vertical ratio because the intensity data cannot be expressed in component form.

Veneziano's direct model and intensity based model are compared in Fig. 4.1.1 for M_{Lg} values of 5,6 and 7, it is observed that the two models are very similar.

Alternatively, one could argue it might be better to take a simpler route than used by Veneziano and choose a relation from (4.1.5) which would balance-off the errors introduced by using an "incorrect" functional substitution and the errors introduced, as discussed in our first GM questionnaire, by using a WUS relation to develop an ENA GM model. If this approach is followed then it is possible to construct a large number of candidate models. To develop such models one only needs to choose some attenuation relation, e.g., several were given in our first questionnaire and Veneziano gives others, coupled with one of the relations (4.1.5). A number of these relations are given and compared in our first questionnaire [See pages C-14 to C-24 of Bernreuter et al. (1985)]. Additional comparisons with other models are given in Section 4.4. In addition, the actual models corresponding to the attenuation relation (4.1.3) and the various GM forms (4.1.5) are also listed in Section 6.

Trifunac argued that the intensity based models just discussed have several problems. Because of the discrete nature of modified the Mercalli intensity scale and no orderly monotonic correlation with GM relation the assumed forms of the attenuation relation (4.1.3) are not appropriate. He also argued that one should avoid introducing magnitude into the problem because, for the most part, the ENA catalogs only have epicentral intensities listed. Trifunac suggested that the Anderson (1978) approach would be the best way to solve the problem.

Very briefly, Trifunac suggests that one use a relation of the form (4.1.5a) to obtain, $P(GM>gm|I_s)$, the probability that the GM level exceeds a value gm given I_s. The $P(I_s|I_0,R)$ can be obtained from the results of Anderson (1978). Anderson studied the distribution of isoseismal contours from existing maps of Modified Mercalli Intensity. From these, he derived a probability function $P(I_S<i|I_0,R)$. The difference of the probability function at two successive points, i and i + I, gives the result needed:

$$P(I_S= i|I_0,R) = P(I_S<i+1|I_0,R) - P(I_S<i|I_0,R) \qquad (4.1.6)$$

Anderson (1978) found that the probability function $P(I_S<i|I_0,R)$ could be approximated by a Gaussian distribution as a function of logR, and found parameters $\mu(I_0,I_S)$, and $\sigma(I_0,I_S)$, the mean and standard deviation, for those combinations of I_0 and I_S where there is enough data.

There are two problems with the actual implementation of Anderson's approach. First, at best the isoseismals only approximately provide the data needed. The actual dispersion is much larger, as one often sees isolated points of I_s one to two units different than the majority of the surrounding data. This in part accounts for the much lower value for σ (0.3) found by Anderson than say by Veneziano who found $\sigma = 1.1$. Secondly, as noted by Anderson there is not enough data for most combinations of I_0 and I_S. Anderson suggested the use of values of $\mu(I_0, I_S) = \log_{10}R(km)$ which satisfy the equation

$$I_S = I_0 + 3.2 - 2.7 \ (\gamma \ \log_{10}e + \log_{10}R), \qquad (4.1.7)$$

where $\gamma = 0.1$/deg for the EUS and $\gamma = 0.6$/deg for the WUS to describe the differences in attenuation rate between these two regions. If one follows this approach then one obtains the usual intensity based GM models discussed in our first GM questionnaire.

Implementation of the model implied by (4.1.6) requires the extrapolation of data to fill in the gaps in Anderson's (1978) Table 4. It is also necessary to judge if the results at the high intensity levels based on only a few points are reliable and, if not, what values for μ (I_0, I_s) and σ (I_0, I_s) should be used?

4.1.3 Spectral Models

Veneziano did not develop models for the relative velocity response spectrum S_v. He did develop models for S_v at 0.1 and 1.0 sec. periods for both his

direct and intensity based approaches. One can form S_v models for use in our analysis based on Veneziano's work by use of the Newmark-Hall spectral model, the ATC spectral model or the RG 1.6 spectral model. See Bernreuter et al., pp C-43-54 for a discussion. Also, in Section 4.4 we make some comparisons between the Newmark-Hall spectral model and other models.

A number of intensity based spectral models can be formed if one uses the approach of combining some intensity attenuation relations (4.1.3) with some spectral relations (4.1.5). At least four relations exist. Trifunac and Anderson (1977) developed a model of the form (4.1.5a) and as part of an earlier project (Bernreuter 1981) we developed two models: one of the form (4.1.5b), and one of the form (4.1.5c). More recently Trifunac and Lee (1985) updated the 1977 Trifunac and Anderson model.

The Trifunac-Anderson and Trifunac-Lee models are a slight departure from the usual form in that they assume a Rayleigh distribution rather then a lognormal distribution. At our workshop Trifunac argued that a Rayleigh distribution fits the residuals much better than a lognormal distribution. The Trifunac-Anderson model was obtained by fitting a relation of the form

$$\log(Sa(f)) = C_1(f) + C_2(f)I_s + C_3(f)\, S \qquad (4.1.8)$$

where f = frequency
Sa = acceleration spectrum
S = 2 (Rock), 1(intermediate rock), 0(deep soil)

to the Cal. Tech. data set.

Some care should be taken if S= 1 or 2 is used in (4.1.8) because most equations for I_s are only valid on deeper soil. See Appendix 1, 2 and Section 5.

Trifunac and Lee (1985) added a number of more recent earthquakes to the Cal.

Tech. set. For a number of these more recent earthquakes, no site intensity data is available. For these cases Trifunac and Lee estimate I_s based on the M_L and R using a relation they developed (Lee and Trifunac (1985)).

Both of the models which we label SEP-1 and SEP-2, and described in Bernreuter (1981), were fit to a modified Cal. Tech. data set. The modification consisted in changing the I_s values associated with given records based on a number of additional factors. Also, the distance from the record to the earthquake was modified to closest approach. This second modification would not, of course, have any impact on relations of the form (4.1.8). The model SEP-1 has the form

$$Ln(Sa(f)) = C_1(f) + C_2(f)\ I_s + C_3(f)\ LnR \qquad (4.1.9)$$

The coefficients $C_i(f)$ are given in Bernreuter (1981) Table (5-4) of Appendix A. The Model SEP-2 has the form

$$Ln(Sa(f)) = C_1(f) + C_2(f) I_s + C_3(f)\ M_L \qquad (4.1.10)$$

and the coefficents $C_i(f)$ are given in Bernreuter (1981), Table 5-3, Appendix C.

In order to illustrate the differences between (4.1.8) (4.1.9) and (4.1.10) we combined each of them with the modified Gupta-Nuttli attenuation of intensity relation. For Eq (4.1.10) we used $M_L = m_b$ based on Hermann and Nuttli (1982). When combining relation (4.1.9) with the Gupta-Nuttli it was assumed that the primary attenuation, as modeled by the coefficent C_3, is due to geometric spreading (most of the Sa-I_s data was recorded at distances less than 100km) which is the same in ENA as in WUS. In Fig. 4.1.2a we compare the Trifunac-Anderson model to the Trifunac-Lee model for m_{Lg}'s of 5, 6 and 7 at an epicentral distance of 10 km and in Fig. 4.1.2b at a epicentral distance of 100 km. In Fig. 4.1.3a we compare the SEP-1 and SEP-2 models at an epicentral distance of 15 km and in Fig. 4.1.3b at a distance of 100 km. Finally, in

Fig. 4.1.4 we compare the Trifunac-Anderson model to the SEP-2 model at an epicentral distance of 10 km.

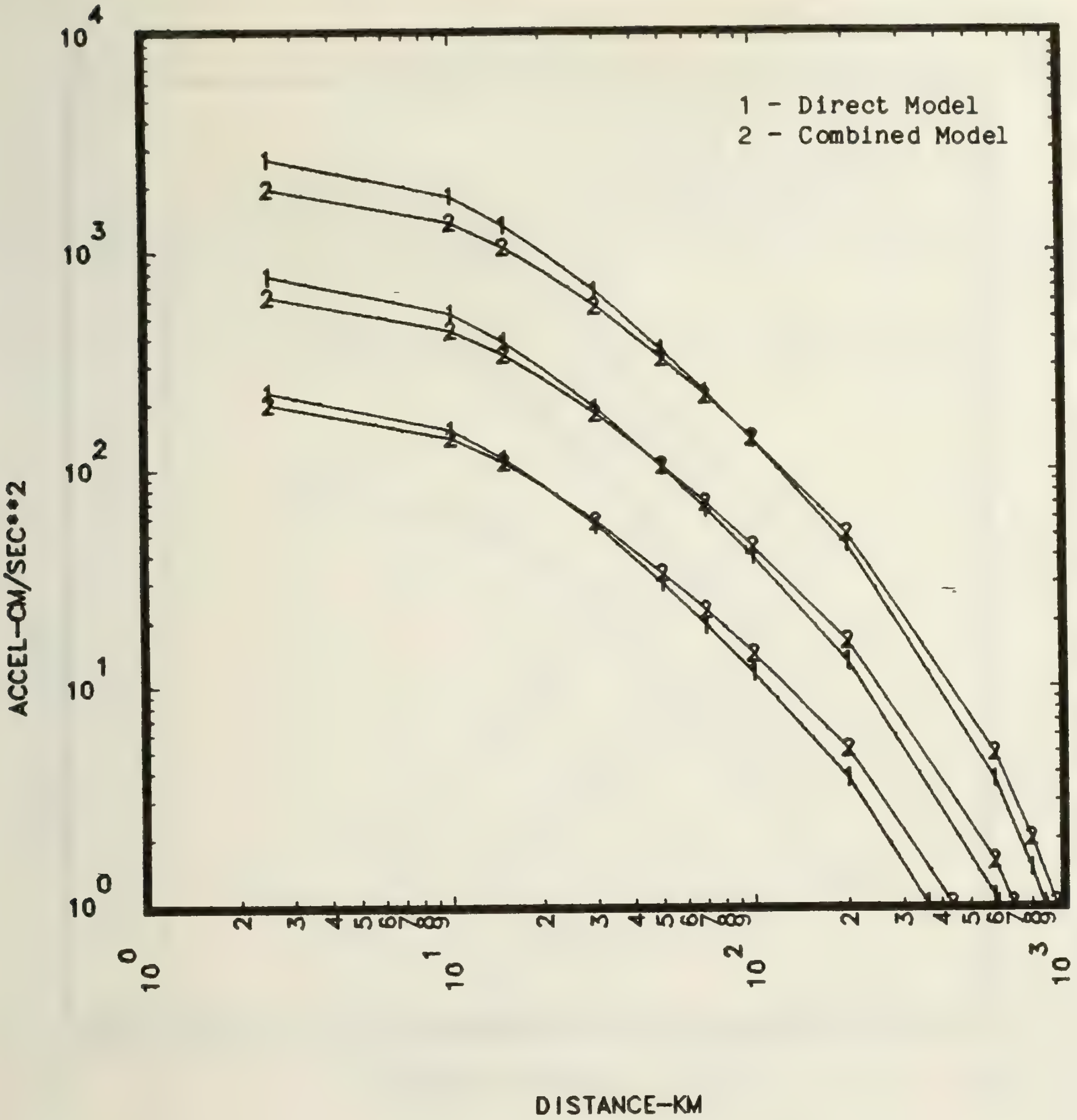


Figure 4.1.1 Comparison between Veneziano's direct regression PGA model and his combined intensity based model for m_{Lg} = 5, 6 and 7 for rock sites.

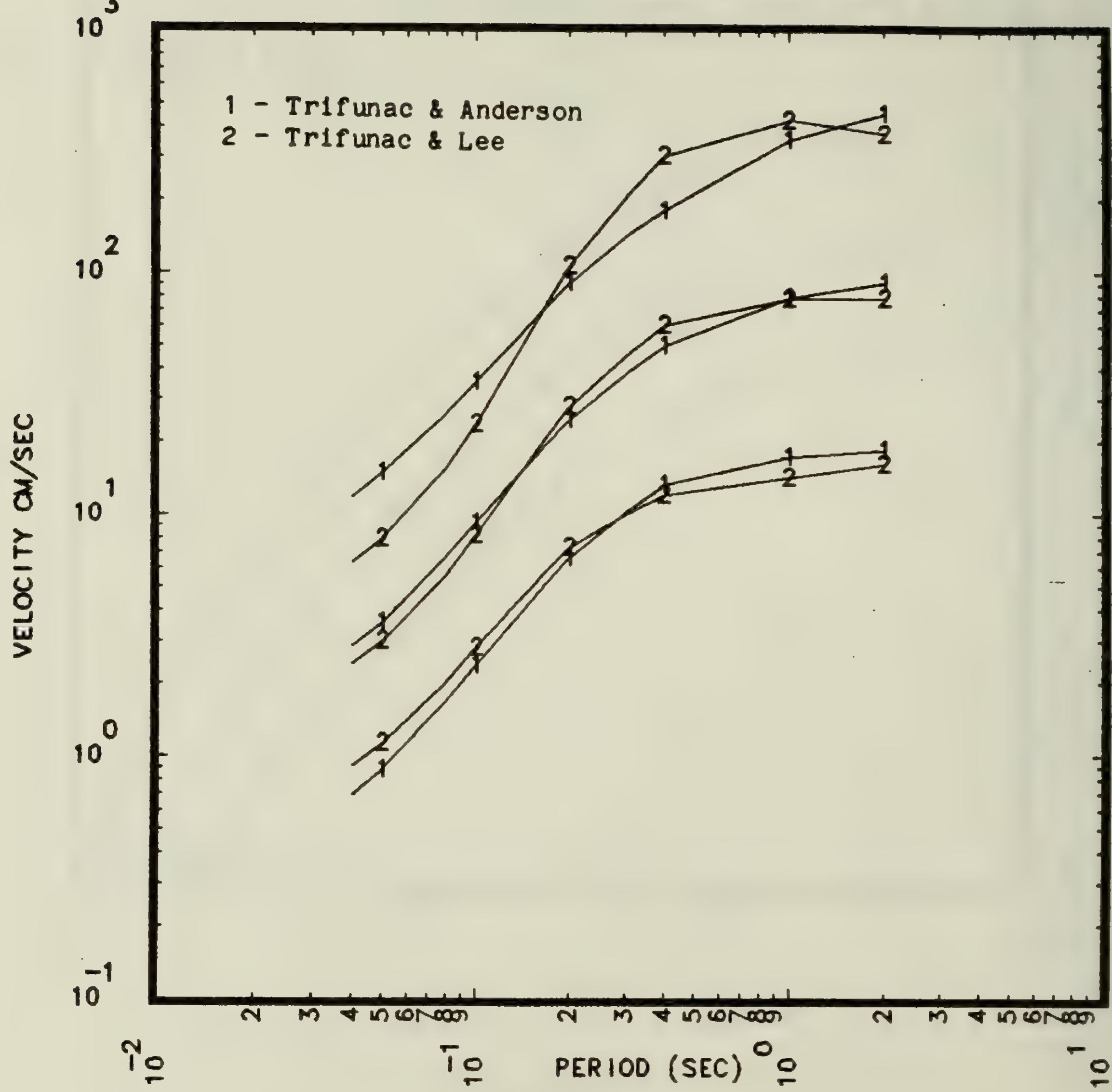


Figure 4.1.2a Comparison between Trifunac and Anderson (1977) 5% damped relative velocity spectral model for m_{Lg} = 5, 6 and 7 at an epicentral distance of 10 km and the Trifunac and Lee (1985) relative velocity spectral model for the same distance and magnitudes for soil sites.

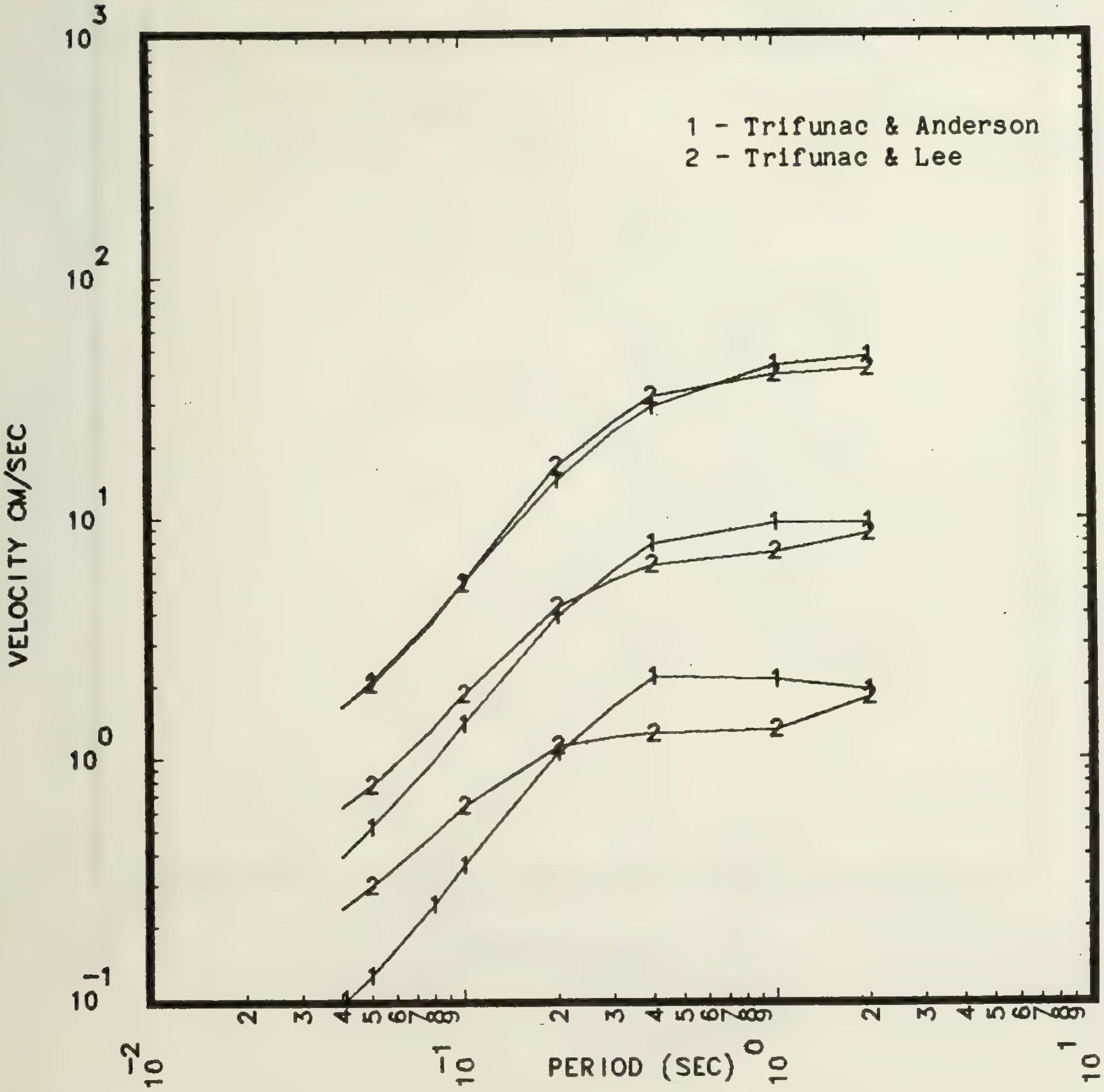


Figure 4.1.2b Same comparison as in Fig. 4.1.2a except at an epicentral distance of 100 km.

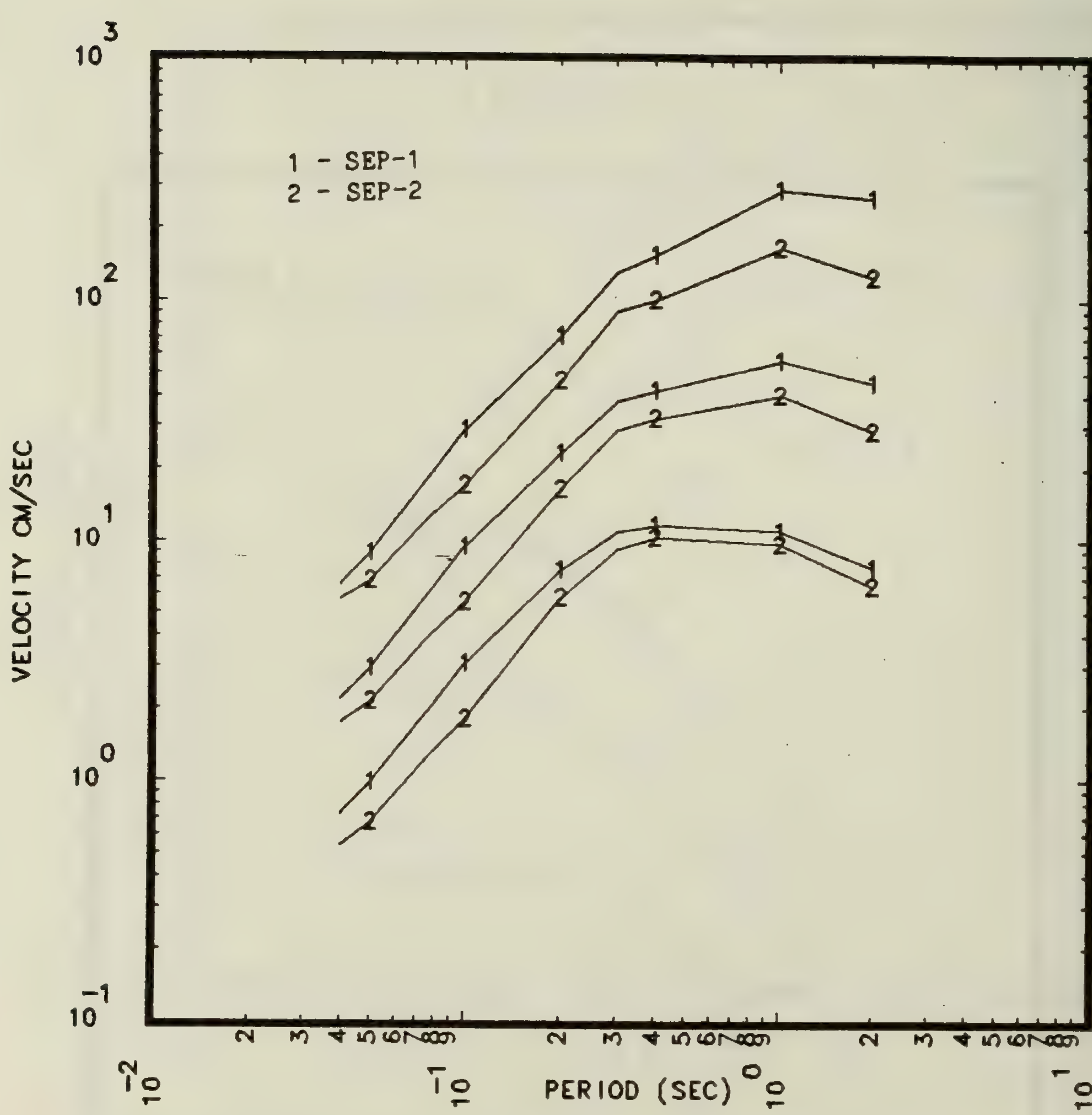


Figure 4.1.3a Comparison between the SEP-1 5% damped relative velocity spectral model and the SEP-2 5% damped relative velocity spectral model for m_{Lg} = 5, 6 and 7 at an epicentral distance of 10 km for soil sites.

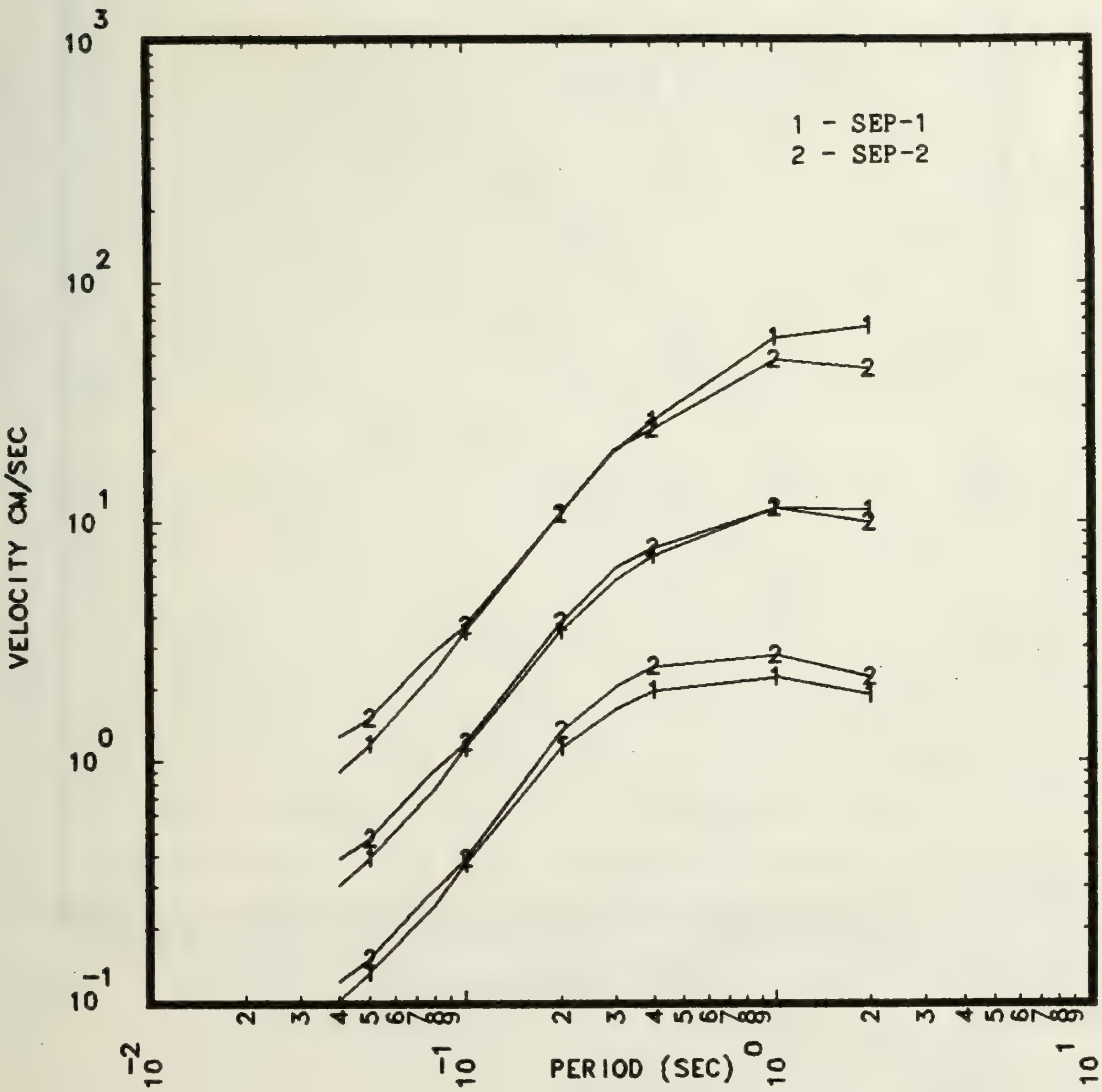


Figure 4.1.3b Same comparison as in Fig. 4.1.3a except at an epicentral distance of 100 km.

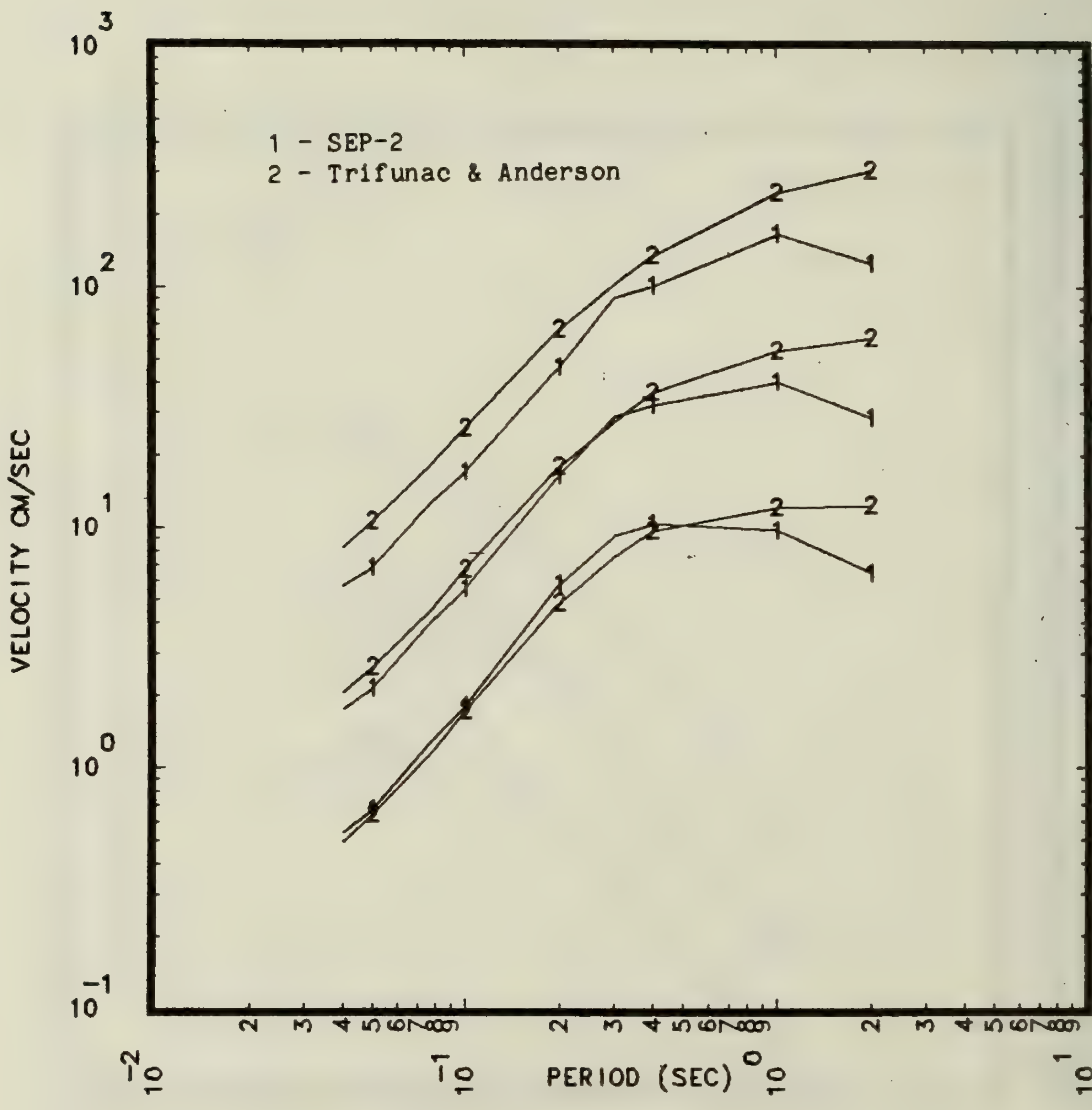


Figure 4.1.4 Comparison between the Trifunac and Anderson (1977) model shown in Fig. 4.1.2a and the SEP-2 model shown in Fig. 4.1.3a for m_{Lg} = 5, 6 and 7 at an epicentral distance of 10 km for soil sites.

4.2 SEMI-EMPIRICAL/THEORETICAL MODELS

4.2.1 General Review of Models

These models rely on empirical data with the somewhat ad hoc interjection of theoretical considerations to complete the model. Models of this type were discussed in our first GM questionnaire [see Bernreuter et al. 1985 pp C-32 to C-42] and cover Campbell's and Nuttli's models. Note that both Campbell and Nuttli have several models. One of Campbell's models is based on the epicentral distance metric and the other is based on the closet approach metric. Nuttli's models are evolutionary, i.e., they are modified in time as his understanding of how best to model the GM of ENA earthquake evolved.

The major conceptual difference between Campbell's and Nuttli's models is that Campbell assumes that GM in ENA scale with magnitude the same as in the WUS such that the only difference in the observed GM between the two regions is due to differences in anelastic attenuation and local site conditions. Nuttli argues that the GM scales differently with magnitude in ENA than in WUS and sets the scaling based on simple theoretical arguments. Nuttli also accepts that there is a difference in anelastic attenuation. Conceptually, the distance metric in Nuttli's models is the hypocentral distance. Nuttli used the available ENA data at the time he developed his models (1979-1983) to determine the free coefficient of his model. Because, as noted in Section 4.1, the strong motion data set is limited to data for few earthquakes around magnitude 5 it is not possible to check Nuttli's magnitude scaling model. In Campbell's model, no "free" parameters are available as the anelastic attenuation parameter is based on regional empirical data. Campbell also compared his model to the data and Nuttli's model. Both models and the data are in reasonable agreement. At the workshop Campbell suggested that his model with the distance metric of closest approach is probably not appropriate, given the metric of our computer program discussed in Section 2. Campbell is not completely happy with his epicentral model, as it is based on older values and models for regional attenuation and he thinks that better models are currently available. See his letter Appendix 4.

Recently Nuttli has revised his model somewhat. Nuttli's reasoning is given in Appendix 3 in a letter to J. Savy. Nuttli now uses a slightly different value for Q in his new model. In addition, he suggests that the scaling of GM with magnitude is somewhat different than for his previous models. Specifically, he had previously based his scaling on the assumption that the corner frequency (f_c) - seismic moment (M_0) curve has a slope of 4. As he discusses in Appendix 3, his current intuitive feeling is that the f_c-M_0 curve will have a slope between 3 and 4 with a most likely value of 3.7 to 3.8. Nuttli provides two bounding models, one for a slope of 4 and one for a slope of 3.5. These two models are compared in Fig. 4.2.1 for m_{Lg} values of 5, 6 and 7. These models were scaled so that they give the same estimate for the PGA at $m_{Lg} = 5$.

It should be noted that Nuttli's (1983) model (see pp C-99-105) of Bernreuter et al.) is only slightly different than the model given in Appendix 3 for a f_c-Mo slope of 4, as is shown in Fig. 4.2.2 where the two models are compared. The difference between the two models lies in the depth term. In the 1983 model the depth term varied as magnitude and in the 1986 model it was fixed at 10km.

4.2.2 Spectral Models

Neither Campbell nor Nuttli developed spectral models. In fact Campbell only developed models for PGA. Nuttli provided models for both PGA and velocity. Campbell's and Nuttli's models can be used as the basis for S_v models by use of either the Newmark-Hall model, ATC model or the RG 1.60 model.

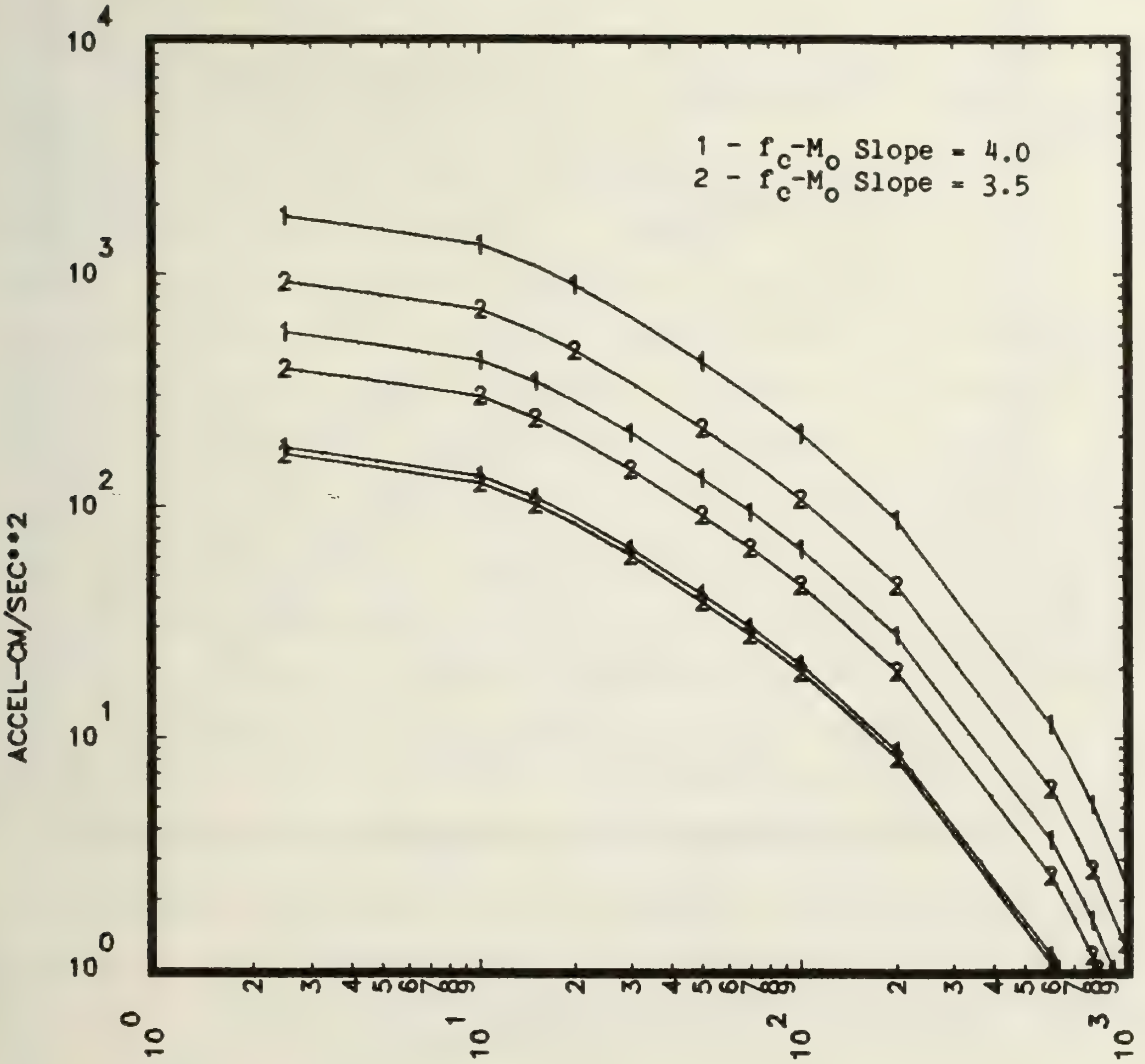


Figure 4.2.1 Comparison between Nuttli's new (Appendix 3) semi-empirical PGA models for m_{Lg} = 5, 6 and 7.

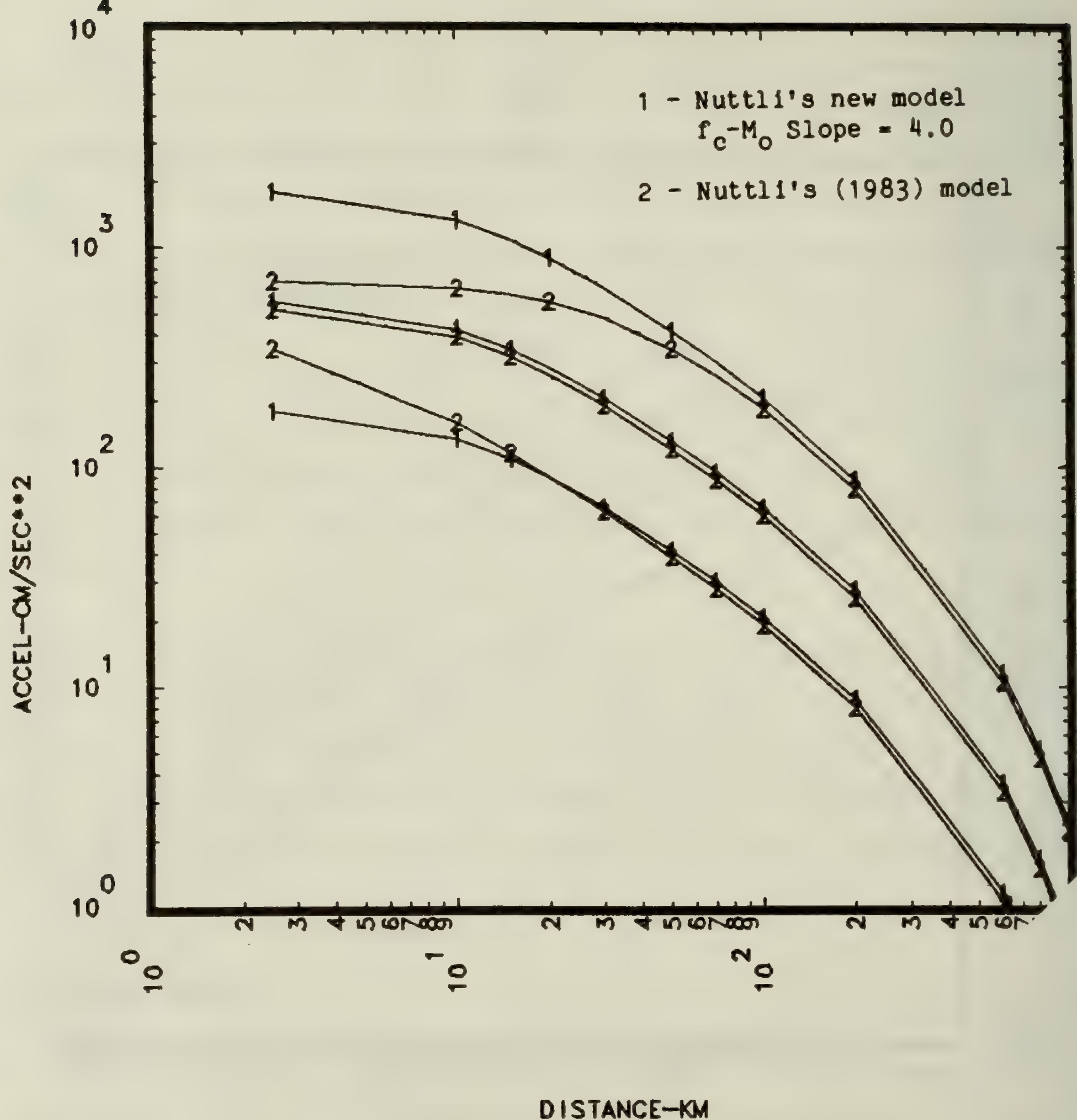


Figure 4.2.2 Comparison between Nuttli's new (Appendix 3) PGA model based on the case with f_c-M_o slope = 4 and the model he suggested in 1983 for m_{Lg} = 5, 6 and 7.

4.3 SIMPLE THEORETICAL MODELS

4.3.1 Review of Models

At our meeting two different but closely related types of simple theoretical models were discussed. The first type is the stochastic simulations (SS) method developed by Boore (1983). The second type employs some results from random vibration (RV) analyses to make estimates of peak ground motion and spectral velocity. Both types start with the same seismological model which defines the Fourier amplitude spectrum as a function of seismic moment, M_0 and corner frequency, f_c. In the SS approach a random phase is introduced along with a normalized shaping window to obtain a simulated time series. Sufficient trials are used to generate statistics on the expected response spectral values for various dampings and peak acceleration and velocity values. In the RV approach, concepts from RV analyses are introduced which allow the peak ground motion and response spectral values to be estimated based on only the Fourier amplitude spectrum of the motion and duration. Boore (1983) showed that the two approaches lead to essentially the same results so that much of the effort in development has been applied to the RV approach.

At our workshop two relatively similar RV models were discussed, namely the Boore and Atkinson (B-A) model and the model developed by Toro and McGuire (T-M) for EPRI. The two models are based on the same basic physical model and only the details are different.

Both the B-A and T-M models start with the far-field Fourier amplitude spectrum form of Brune's (1970) model to relate the spectral shape and level to M_0 and f_c. The high frequency end is truncated with a filter at f_m. Parseval's theorem is used to relate the RMS value to M_0, f_c and f_m. In order to make the RV model a single parameter model both B-A and T-M assume that M_0-f_c are related such that

$$f_c{}^3 M_0 = \text{constant} \qquad (4.3.1)$$

i.e., the f_c-M_0 curve has a slope of 3 on a log-log scale. This is a key assumption generally made for WUS earthquakes. On the other hand, as discussed in Section 4.2 and Appendix 3, Nuttli argues that the data are better fit by a slope closer to 4 than 3. Following Brune's model Eq. (4.3.1) implies a constant static stress drop. The model proposed by Nuttli,

$$f_c{}^4 M_0 = \text{constant} \qquad (4.3.2)$$

would have the stress drop increasing with M_0. Both B-A and T-M assume the same constant for (4.3.1). Up to this point no RV concepts have been introduced. However, to go from the first moment of the spectrum (RMS value) to the peak value of the GM requires the introduction of RV results. Specifically both B-A and T-M use the RV relation

$$[\text{peak}] = [\text{RMS}] \; [P_f] \qquad (4.3.3)$$

After this point the B-A model differs from the T-M model. In the T-M model the approximate relations

$$P_f = [2\mathrm{Ln}(N)]^{1/2} + 0.577/[2\mathrm{Ln}(N)]^{1/2} \qquad (4.3.4)$$

$$N = \max\,[2f_D T,\ 1.33] \qquad (4.3.5)$$

where

T = duration parameter

f_D = predominant frequency

are used. For large N, B-A also use 4.3.4 but for smaller values of N, B-A use the exact relation- Eq. (21) in Boore (1983). Equation 4.3.4 is an approximation of Boore's Eq. (21) for large N. The use of (4.3.4) appears to

lead to slightly lower estimates of the peak as compared to the more exact formulation. When N is sufficiently small so that B-A use Boore's Eq. (21) to compute P_f, then B-A also use a different relation to estimate f_D than T-M. When B-A use (4.3.4) to compute P_f then B-A use the same equation as T-M to compute f_D.

More importantly T-M use a different relation to estimate the duration T than B-A. Specifically B-A used

$$T = \frac{1}{f_c} + 0.05R \qquad (4.3.6)$$

whereas T-M used

$$\begin{aligned} T &= \frac{1}{f_c} && R < 100 \\ &= \frac{1}{f_c} + 0.1\,(R-100) && 100 < R < 200 \qquad (4.3.7) \\ &= \frac{1}{f_c} + 0.05R && R > 200 \end{aligned}$$

The difference in the choice of T is important with the B-A choice leading to lower values for the peak, with the difference increasing with R.

In Eq. (4.3.3) the RMS is a function of M_o. For use in a hazard analysis a relation between M_o and m_{Lg} is needed. Rather than use some empirical relation both B-A and T-M used their RV models to compute the peak amplitude and characteristic frequency of the seismic motion for given types of seismic instruments. Then the equivalent magnitudes were computed from standard formulas. However, B-A and T-M chose different formulas. B-A used Nuttli's (1973) definition and T-M used the relation developed by Herrmann and Kijko (1983). Because the RV approach only models the horizontal component of GM and the equations for m_{Lg} are for the vertical component both B-A and T-M used a 0.7 factor to convert the horizontal to vertical. This conversion factor is significantly different from the value given in Table 4.1 found by

Veneziano. However, Veneziano had relatively few stations with both horizontal and vertical components. Given the large variability of the H/Z ratio for different stations the two sets of numbers are not necessarily in conflict.

Both B-A and T-M used the same model for Q. However, the model used

$$Q = 500\ f^{a} \qquad a = 0.65 \tag{4.3.8}$$

is different than the model assumed in the development of the equations used to compute the magnitude. This introduces a problem in the development of the M_o - m_{Lg} relation. T-M chose to compute m_{Lg} at 200 km whereas B-A chose 800 km. In addition, B-A computed m_{Lg} for a given M_o for several instrument types and averaged. T-M only used the WWSSN instrument. The difference in instrument type, formula, and distance used introduces a significant uncertainty into the M_o - m_{Lg} relation which is not incorporated in either the T-M or B-A models. As a net result of the differences between the RV models and equations used to compute the magnitude from the amplitude of the computed GM, B-A and T-M arrive at different M_o - m_{Lg} relations which are plotted on Fig. 4.3.1. In the hazard analysis one has m_{Lg} and needs to convert it to M_o for use in the RV model. Thus it is seen from Fig. 4.3.1 that for a given m_{Lg} the corresponding M_o used in the T-M model is generally smaller than the B-A M_o. However for both large and small earthquakes the differences between the relations is smaller. The largest differences between the two relations occurs around $m_{Lg} = 6$ where the difference in Log M_o between the T-M and B-A models is almost 0.5 units.

The difference between the B-A M_o - m_{Lg} relation and the T-M M_o - m_{Lg} relation is due primarily to the different procedure used to compute an m_{Lg} from the amplitude of GM rather than differences between the RV models. This uncertainty in the computed magnitude using the RV model is even larger if the

uncertainty in the appropriate value for conversion of the average horizontal component of GM to the vertical is accounted for. Street and Turcotte (1977) suggested that the H/Z ratio should be 3 i.e., similar to the value found by Veneziano, whereas both T-M and B-A used 1.4.

Hanks and McGuire (1981) showed that

$$\text{Log (PGA)} \approx 1/5 \log M_0.$$

Thus the maximum difference in the estimate of the PGA between the B-A and T-M RV models due only to the difference in the relation between m_{Lg} and M_0 used is about 25%. It should be noted that there are a number of other differences between the B-A and T-M models hence the net effect of all of these factors is different than any single factor.

Two additional differences between the T-M and B-A models are in the choice of the constants giving the average radiation pattern, free surface effects and the partition of a vector into horizontal components and (2) the appropriate value for the density. T-M use 2.5 g/cc and B-A use 2.7 g/cc. This factor alone makes the T-M estimate 1.08 times larger than the B-A estimate. The difference in constants makes the T-M estimate 1.04 times larger than the B-A estimate. Potentially, the choice of the shear wave velocity is even more significant as the GM scales inversely as the cube of the shear wave velocity. Both B-A and T-M used 3.8 km/s for the shear wave velocity. Clearly, the choice of both the appropriate density and shear wave velocity is some what arbitrary.

In summary, the assumptions that must be introduced into both the SS and RV models are the choices for density, shear wave velocity, duration, the relation between M_0 and f_c and finally the relation between M_0 and m_{Lg}. Figure 4.3.2 gives a comparison between the B-A and T-M models. Their models are in reasonable agreement, however, it must be kept in mind that the two models use very different relations for converting m_{Lg} to M_0 as shown in Fig.

4.3.1. If both T-M and B-A used the same equation to relate M_o-m_{Lg} then their two models would differ more significantly.

The two most controversial assumptions are the choices for the relation between M_o and m_{Lg} and for the relation between M_o and f_c.

No matter what M_o-f_c relation is used, one needs a relation between M_o and m_{Lg} to use the RV model. As discussed above, this relation is the source of significant uncertainty. It is also possible to question the validity of B-A's and T-M's approach to compute the M_o-m_{Lg} relation using the RV model. One possible objection is that at the regional distances at which m_{Lg} is computed the RV spectra used in the computation may not be applicable. Based on the results given in Haar et al. (1986), it would appear-that the regionally recorded L_g spectra (generally used in the CUS to compute m_{Lg}) are significantly different from the "local" body wave spectra which are the spectra modeled by the RV model. In particular, as illustrated by Fig. 4.3.3 adapted from Haar et al. (1986) by Atkinson, the corner frequencies are different and it appears that the spectral level at 1Hz are lower for the regionally recorded ground motion (after correction for attenuation) than for locally recorded spectra. Because many instruments, in particular the WWSSN typically used to compute m_{Lg}, are peaked around 1-2 Hz the RV model should result in a larger estimate of m_{Lg} for a given M_o than one might obtain using the regionally recorded L_g spectra. This could account for some of the differences between either the B-A or T-M m_{Lg}-M_o relations and Nuttli's empirical m_{Lg}-M_o relation which is also plotted in Fig. 4.3.1. It is seen from Fig. 4.3.1 that for a given seismic moment, Nuttli's empirical relation gives a lower m_{Lg} value than either the B-A or T-M relations. Figure 4.3.4 illustrates the significance of the M_o-m_{Lg} relation. Figure 4.3.4 shows the PGA for the B-A RV model for the case when the B-A M_o-m_{Lg} relation is used and the case when the Nuttli M_o-m_{Lg} relation is used.

It is of some interest to examine what happens to the prediction of GM when various choices are made for the parameters a and c in the relation

$$M_0 f_c^{a} = c \qquad (4.3.10)$$

As previously noted, both T-M and B-A chose a = 3.0 and c to correspond to a stress drop of 100 bars. Figure 4.3.3 shows B-A and T-M's M_0-f_c relation relative to the data. Also shown is Nuttli's (1983) relation

$$M_0 f_c^{4} = 15.9 \times 10^{21} \qquad (4.3.11)$$

Equation (4.3.11) is based on f_c determined using L_g spectral data which Nuttli agrees is too low (Appendix 3). It is evident from Fig. 4.3.3 that the data do not constrain the parameters a and c in (4.3.10) very well. One could also infer that the 100 bar stress drop model does not fit the data very well either. It should be noted that for the WUS data Boore (1986) has modified his RV model to include site amplification which then leads to a stress drop of 50 bars and would move the M_0-f_c relation over in the data. There is so little ENA data that it is difficult to use then to constrain the parameters of the model because, as noted, what little data that exist have often been recorded at sites where one might expect significant site amplification.

To provide you with some information on the sensitivity of the estimated GM due to the changes in the parameters, a and c of Eq. (4.3.10), the following three somewhat arbitrary choices were made:

(1) Choose c to keep the f_c-M_0 relation the same as for the constant stress drop model with $\Delta\sigma$ = 100 bars at approximately m_{Lg} = 5 (where the bulk of the ENA data exist) and take Nuttli's preferred value of 3.75. The resultant relation is also shown in Fig. 4.3.3 as model 1.

(2) Keep a = 3.75 but choose the constant c so that the M_0-f_c curve fits the bulk of the M_0 - f_c data. This relation is also shown in Fig. 4.3.3 as model 2.

(3) In order to show the sensitivity to the parameter a, the parameter c was given the same value as for model (2) but a = 3.5 was used. This relation is also plotted in Fig. 4.3.3 as model 3.

As discussed earlier there are a number of ways to obtain a M_0-m_{Lg} relation so that comparisons between models can be made relative to the m_{Lg} scale. Because of the variation in the computed m_{Lg} value due to the choice of equations and distances that could be used to evaluate m_{Lg} and of the possible variations between regional L_g spectra and the RV model spectra, we opted to use Nuttli's empirical relation

$$\text{Log } M_0 = 2\, m_b + 13.2 \qquad (4.3.12)$$

and assume that $m_{Lg} = m_b$ on the average.

Figure 4.3.5 gives a comparison between models (1), (2) and (3) for $m_{Lg} = 5$ and 7. It is observed from Fig. 4.3.5 that changing the power of f_c (the parameter a in (4.3.10)), changes the GM scaling with magnitude (or M_0). Figure 4.3.5 also shows that changing the constant c shifts the relative location of the curves for GM for a constant magnitude.

It is of some interest to note that taking a = 3.75 leads to Ln (PGA) scaling as approximately 1.7 m_{Lg} and a = 3.5 leads to scaling as approximately 1.5 m_{Lg} for the RV model. This scaling is larger than the scaling found by Nuttli in his semi-empirical model, e.g., for a = 3.5. Nuttli suggested that Ln (PGA) should scale between 0.86 m_{Lg} and 1.15 m_{Lg}. Veneziano found (Table 4.1.1) that Ln (PGA) scales as approximately 1.2 m_{Lg}. If some other M_0-m_{Lg} relation is used then the scaling of PGA with magnitude changes depending upon the choice of the relation. For example, in what we label model 4, a M_0-m_{Lg} relation was computed using the same approach as used by T-M (the use of R = 200 km and the same formula to compute m_{Lg}) for an RV model with parameter a = 3.5 and constant c chosen so that the f_c-M_0 values are the same at m_{Lg} approximately 5, as for model 1 shown in Fig. 4.3.3. For model 4 we find that

Ln (PGA) scales as approximately 1.28 m_{Lg}. The M_0-m_{Lg} relation is shown in Fig. 4.3.1 as the curve labeled model 4.

By properly choosing the constant c in (4.3.10) one can match the available strong GM data from ENA earthquakes. However, as noted earlier, all of the data are from earthquakes of approximately the same magnitude. Thus the choice of parameters for (4.3.10) and the M_0-m_{Lg} relation has to be based on judgment. For example, in Fig. 4.3.6 we compare the RV form of the B-A model to model 4 described above for m_{Lg} values of 5, 6, and 7. Clearly, we could not reject either model on the basis of the existing ENA strong motion data set.

4.3.2 Spectral Models

Because the RV-models start with a Fourier amplitude spectrum it is a relatively simple task to develop a model for the 5 percent damped relative velocity spectrum. B-A correct for duration effects when the estimated duration is shorter than the period of the oscillation slightly differently than T-M. The differences in correction between B-A and T-M are relatively unimportant when compared to the more important differences in how duration is estimated, Eq. (4.3.6) as compared to Eq (4.3.7), and how the M_0-m_{Lg} relation is computed. However, the difference in how the correction is made for the duration effect shows up at the longer spectral periods as shown in Fig. 4.3.7a where the 5 percent damped S_v spectra obtained from the T-M model for m_{Lg}= 5,6 and 7 at an epicentral distance of 10 km are compared to the S_v spectra obtained from the B-A model for the same magnitude range and distance. In Fig. 4.3.7b the same comparison is made at 100 km. At 10 km the two models are in good agreement. At 100 km the differences between the models are more significant, however, the differences most likely would only have a minor impact on the estimated hazard at a site.

In Fig. 4.3.8 we compare S_v for m_{Lg}= 5,6 and 7 for models 2 and 3 discussed above. For model 2 the parameter a in Eq. 4.3.10 is equal to 3.75 and for

model 3 a = 3.5. For both models the constant c is the same. The Nuttli M_o-m_{Lg} relation was used. The major difference between the two models is in the way S_v scales with m_{Lg}. In Fig. 4.3.9 we compare the S_v for model 3 to the S_v for the B-A model at 10 km for m_{Lg} = 5 and 7. At m_{Lg}=5 one can also observe the impact of the relation between M_o, m_{Lg} and f_c on the spectral shape. At m_{Lg} = 7 we do not observe this effect in large part because the plotted range of 0.04 to 2.0 sec. does not include the corner period.

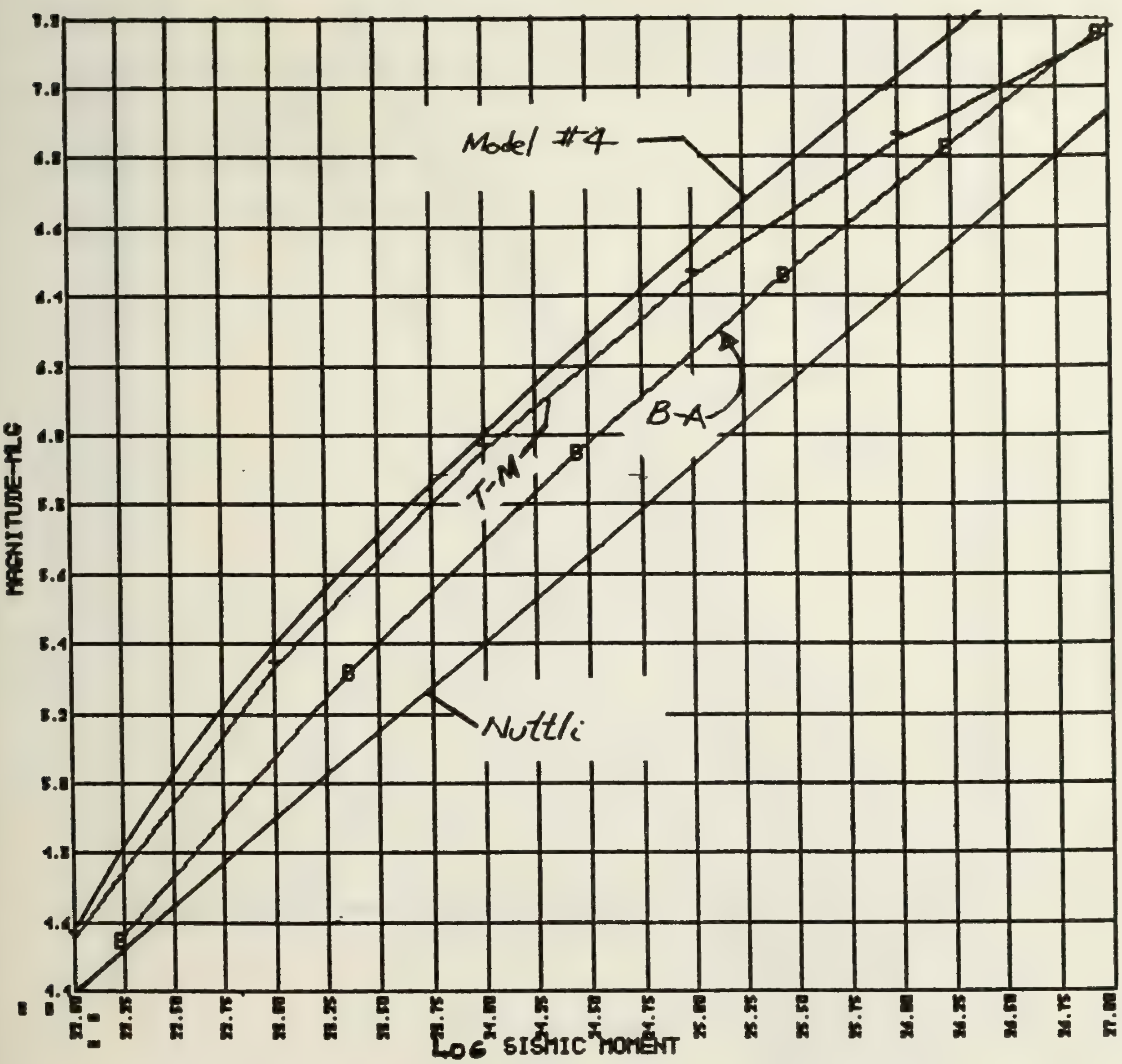


Figure 4.3.1 Comparisons between Nuttli's empirical m_{Lg}-Log (M_o) relation and the relations used by T-M and B-A.

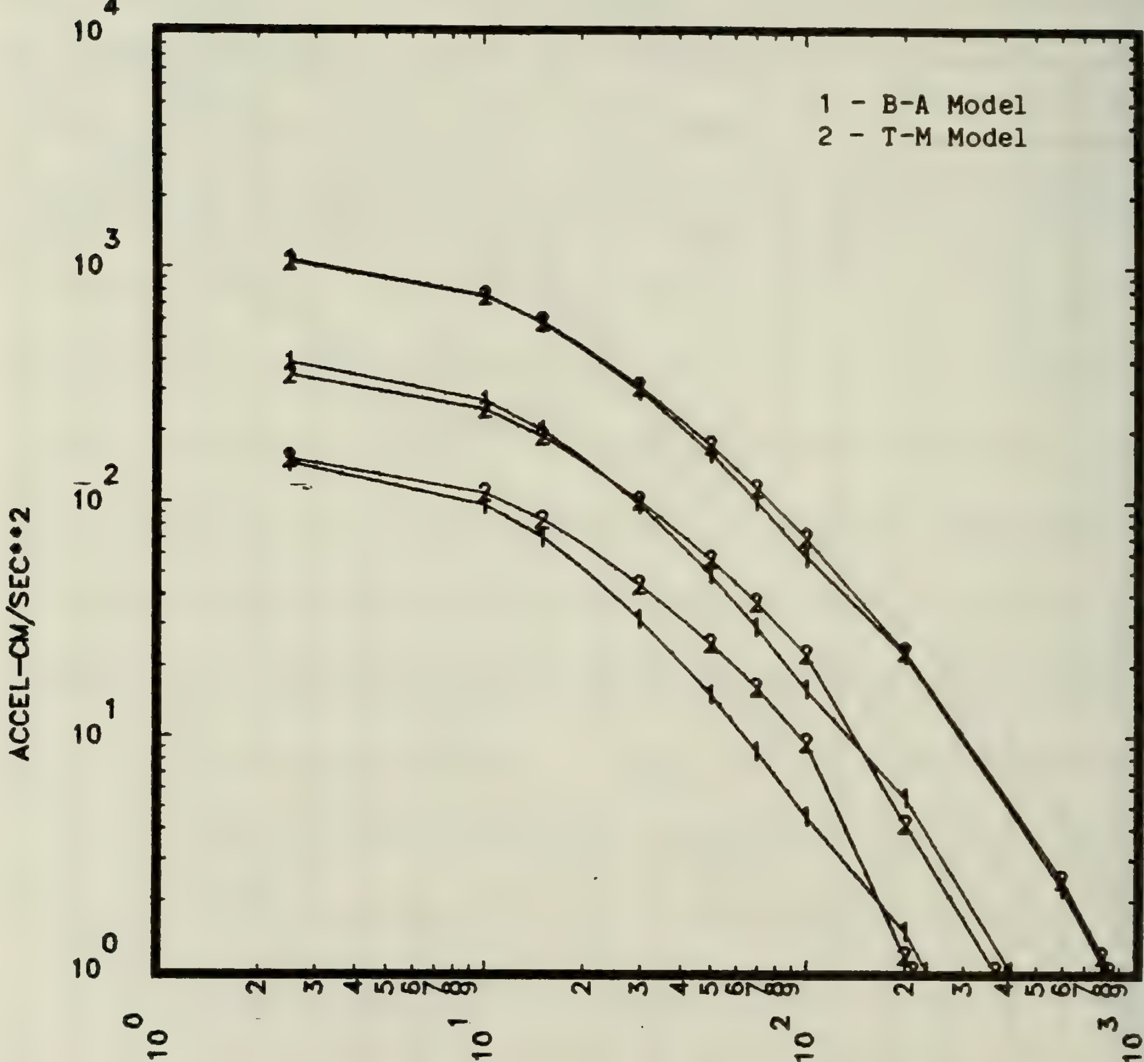


Figure 4.3.2 Comparison between the B-A and T-M PGA models for m_{Lg} = 5, 6 and 7.

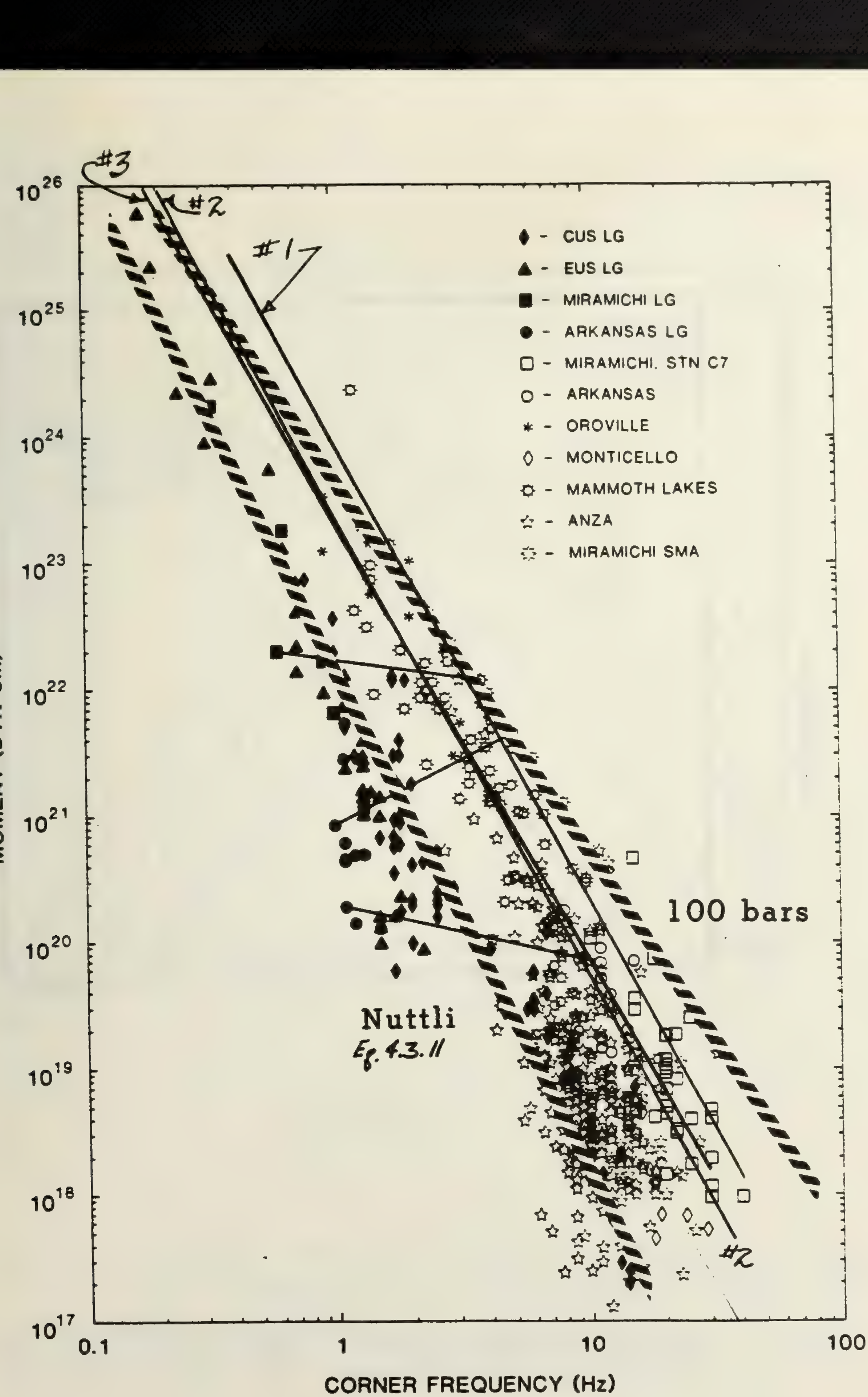

#3
#2
#1
CUS LG
EUS LG
MIRAMICHI LG
ARKANSAS LG
MIRAMICHI. STN C7
ARKANSAS
OROVILLE
MONTICELLO
MAMMOTH LAKES
ANZA
MIRAMICHI SMA
100 bars
Nuttli
Eq. 4.3.11
#2
MOMENT (DYN CM)
CORNER FREQUENCY (Hz)
0.1
1
10
100

Figure 4.3.3

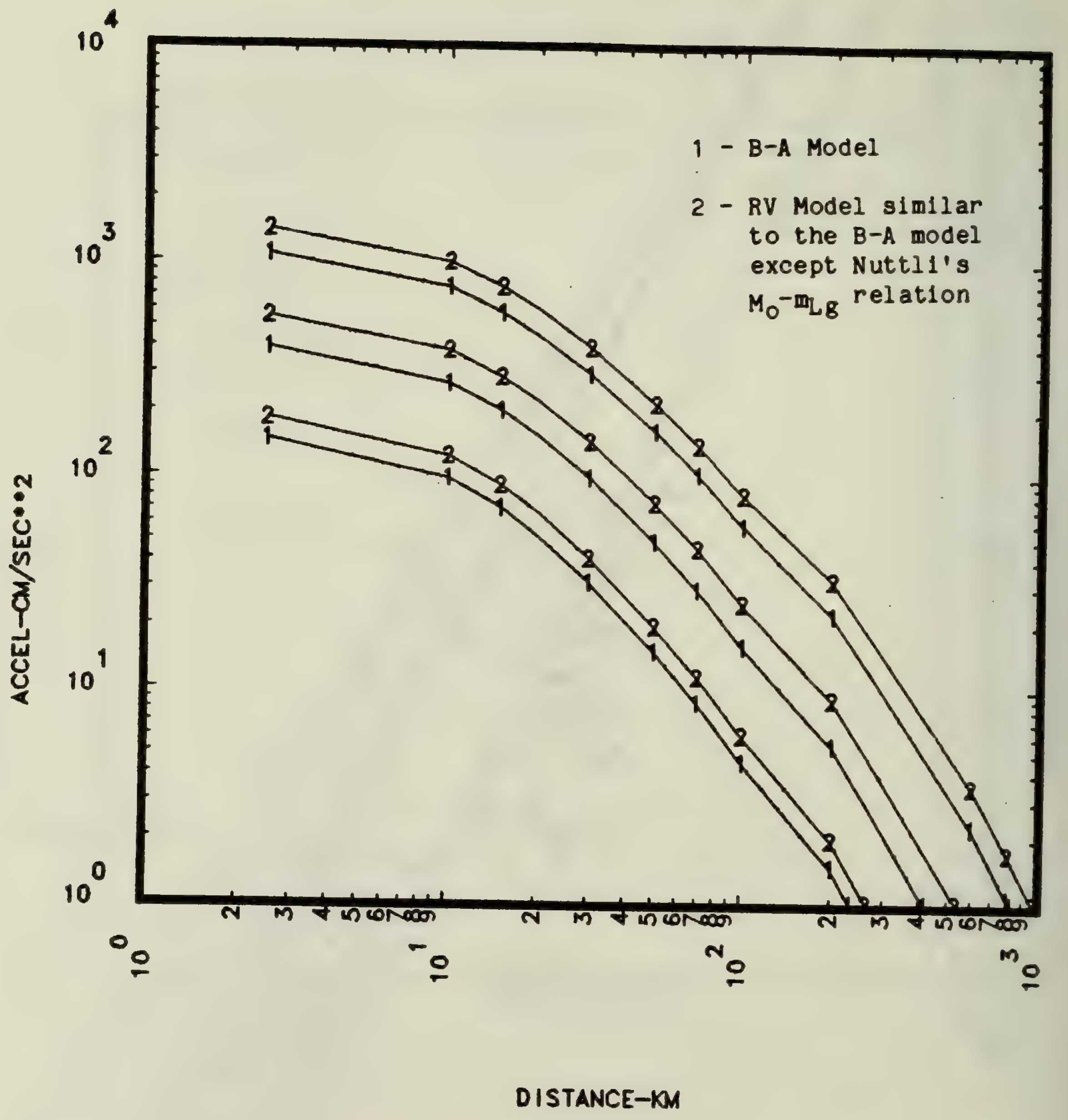


Figure 4.3.4 Comparison between the B-A PGA model and a RV model similar to the B-A model except the empirical Nuttli M_o-m_{Lg} relation was used in place of the B-A M_o-m_{Lg} relation shown in Fig. 4.3.1.

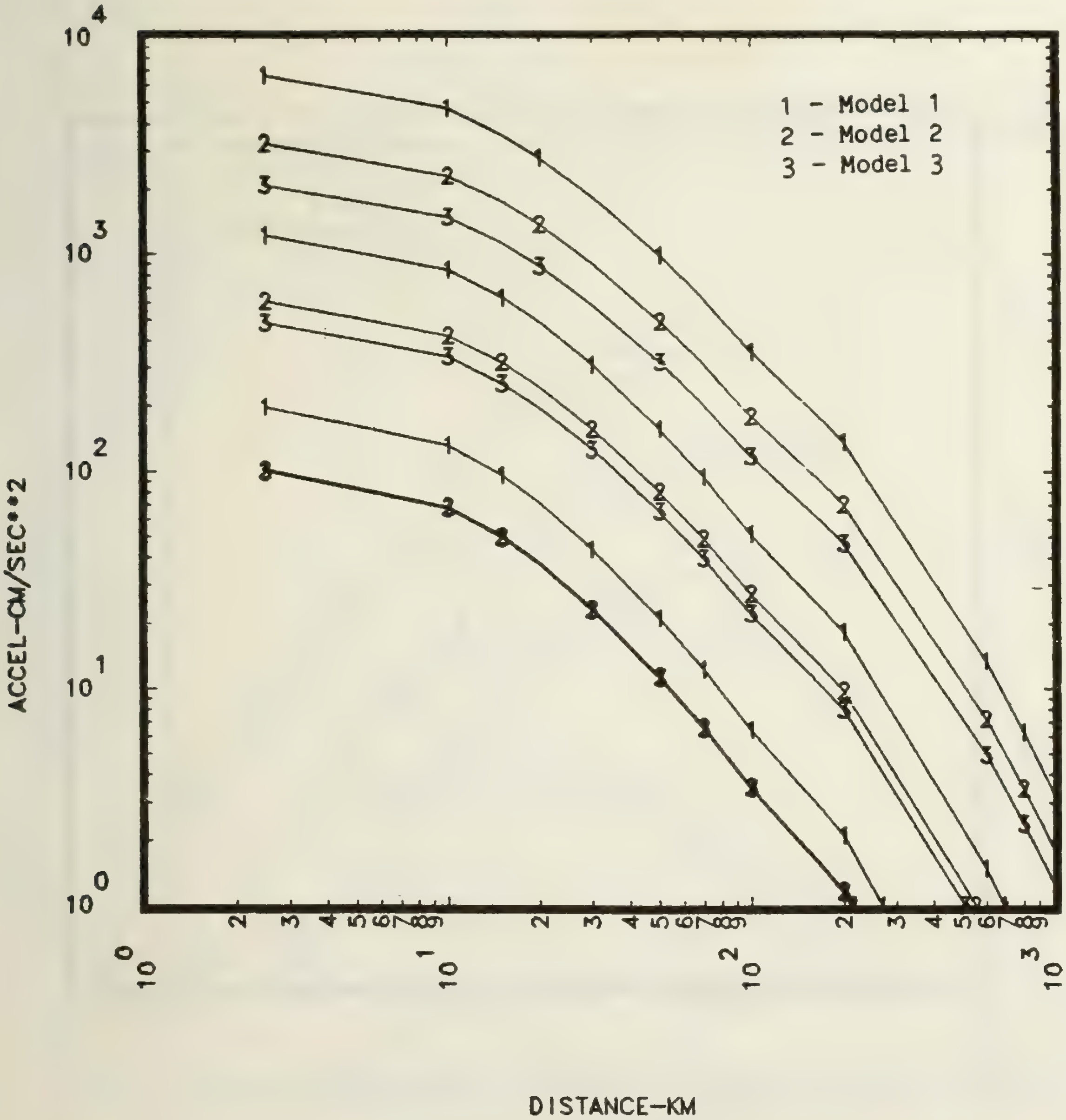


Figure 4.3.5 Comparison between RV Models #1, #2, and #3 described in the text for m_{Lg} = 5, 6 and 7. Models #1 and #2 have a f_c-M_0 slope of 3.75 and Model #3 has a f_c-M_0 slope of 3.5

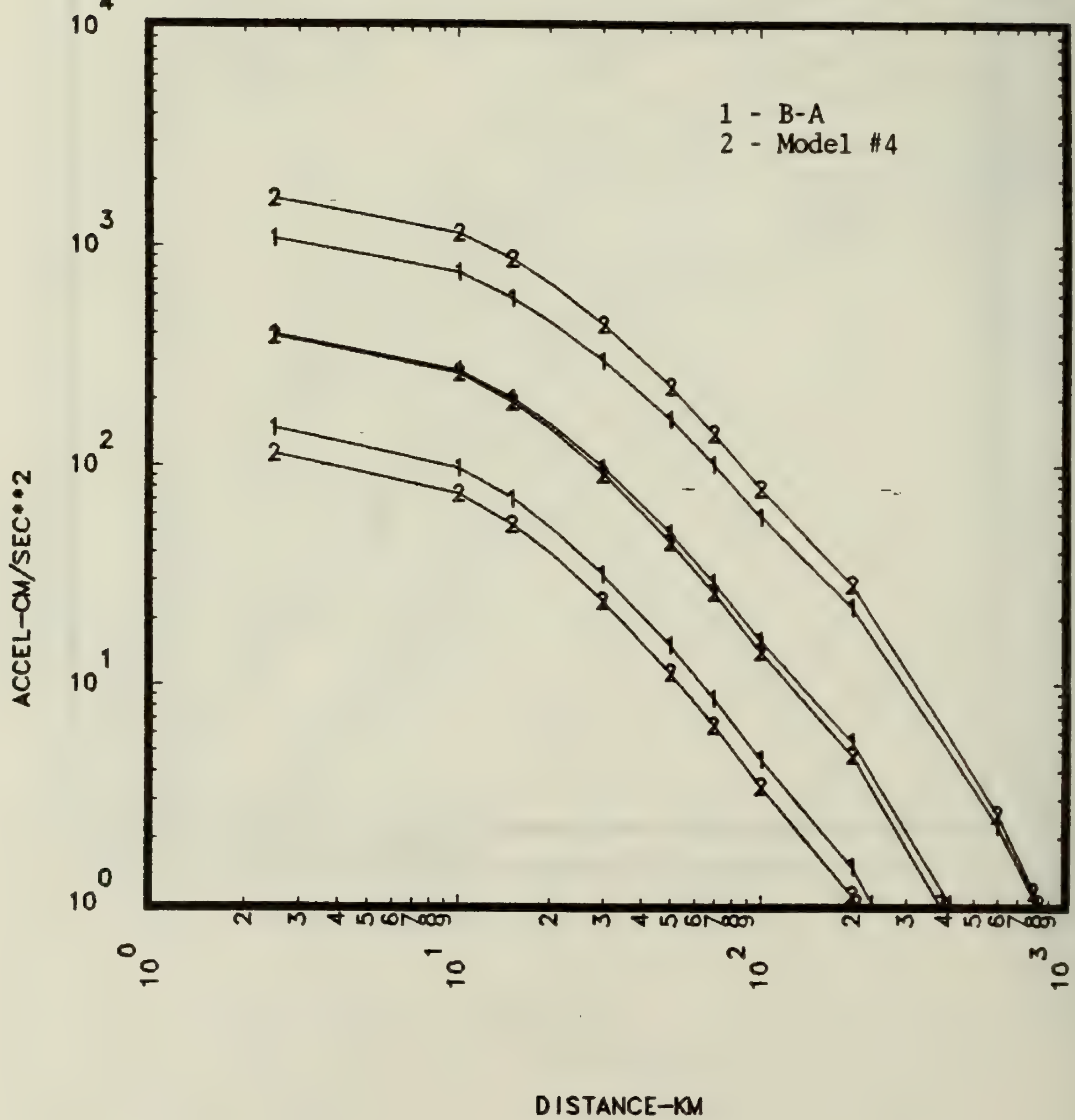


Figure 4.3.6 Comparison between the B-A model and RV model #4 for m_{Lg} = 5, 6 and 7. RV Model #4 is based on a M_0-f_c slope of 3.5 and the m_{Lg}-M_0 relation was computed as described in the text.

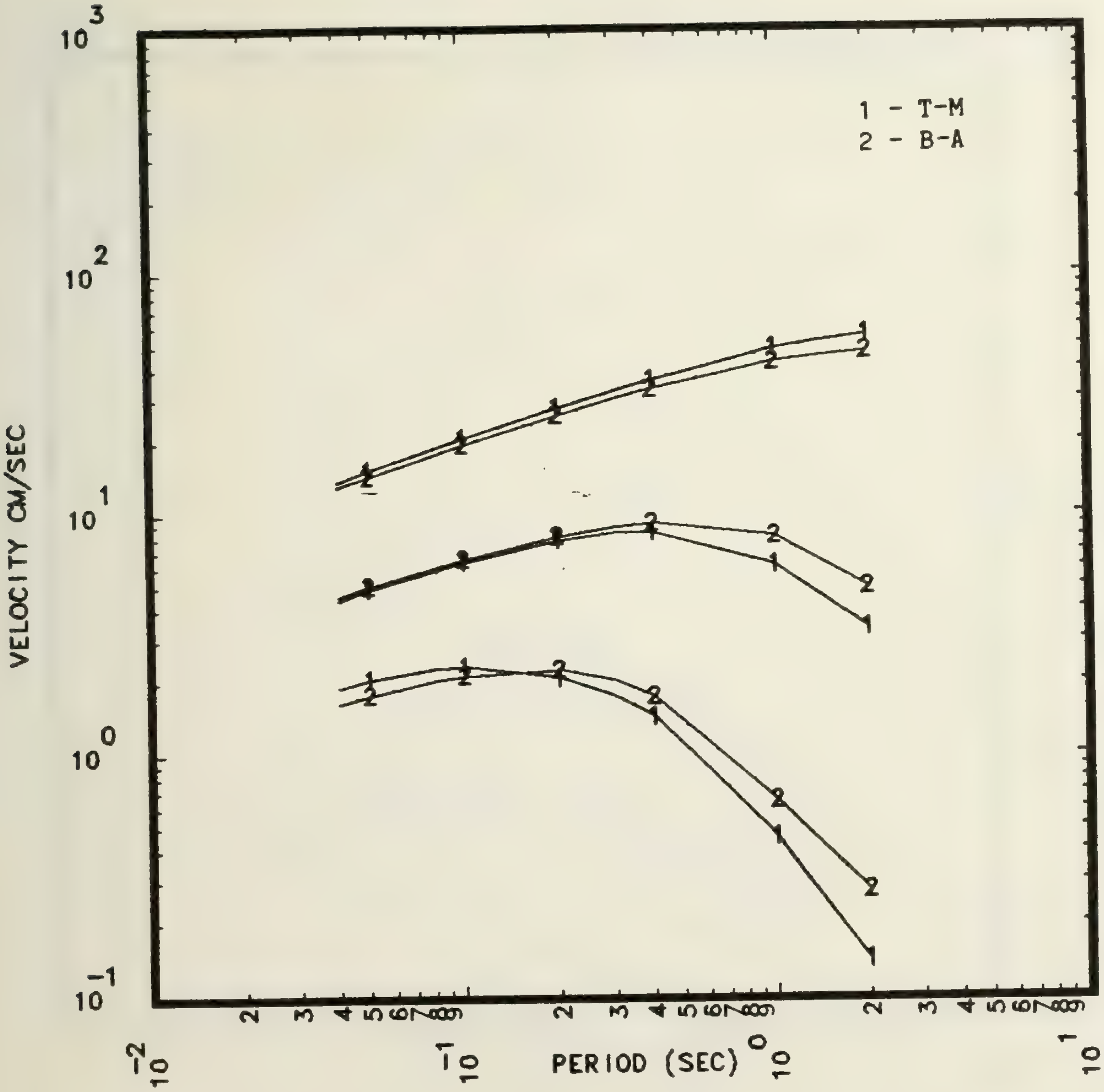


Figure 4.3.7a Comparison between the T-M and B-A 5% damped relative velocity spectral models for m_{Lg} = 5, 6 and 7 at an epicentral distance of 10 km.

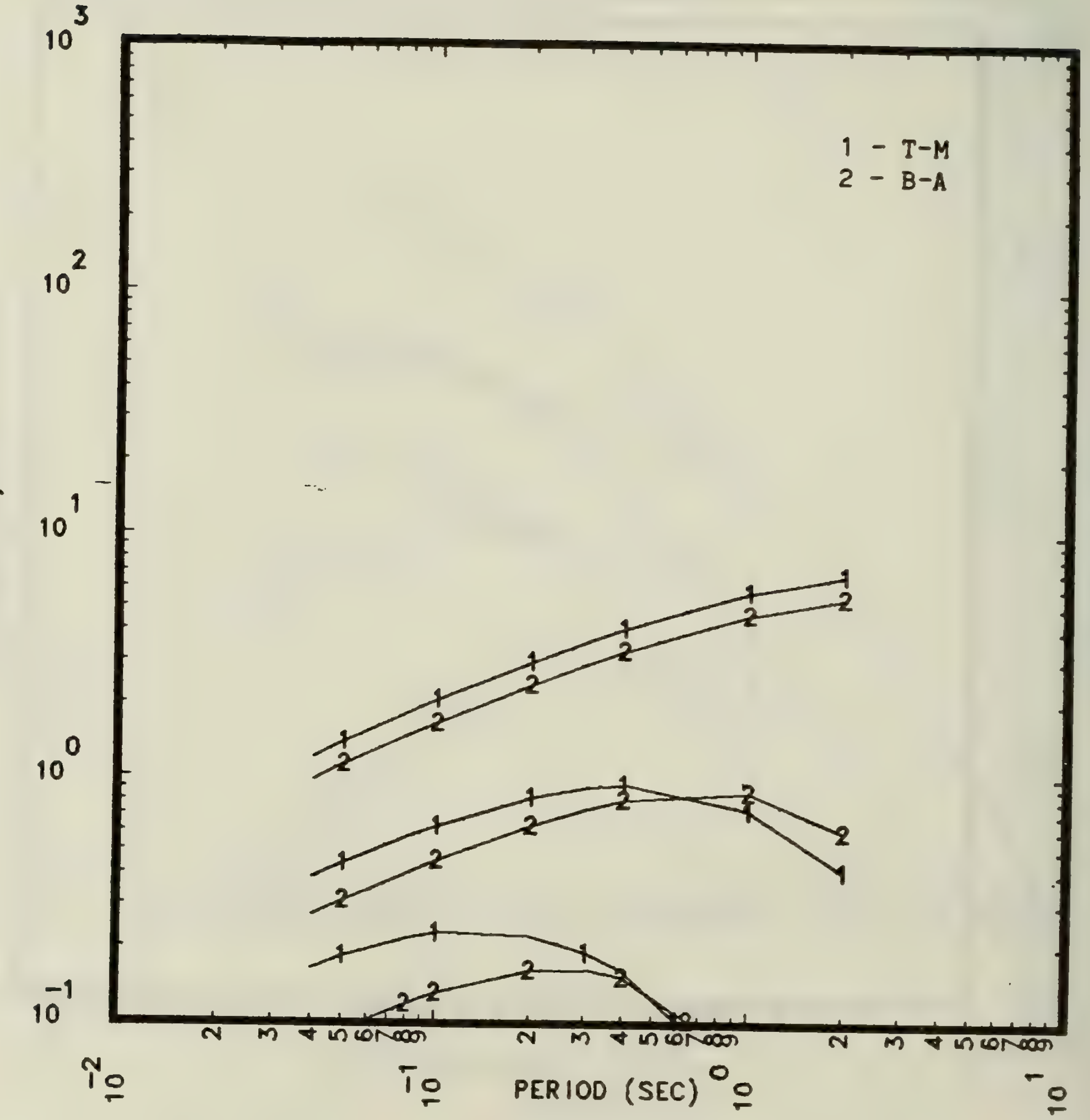


Figure 4.3.7b Same comparison as in Fig. 4.3.7a except at an epicentral distance of 100 km.

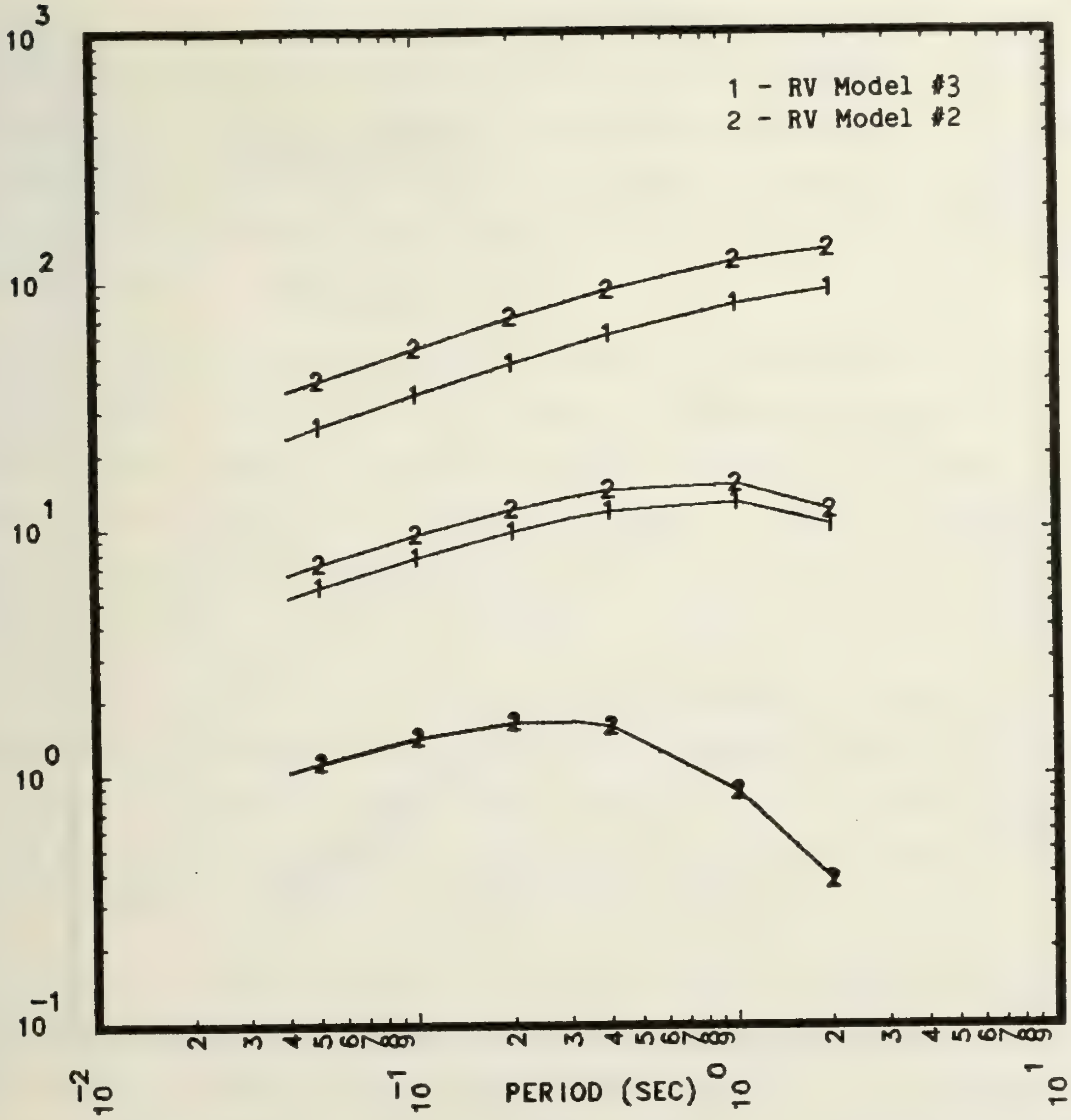


Figure 4.3.8 Comparison between the 5% damped relative velocity spectral models #2 and #3 for m_{Lg} = 5, 6 and 7 at an epicentral distance of 10 km. RV Model #2 is based on a f_c-M_0 slope of 3.75 and RV Model #3 is based on a f_c-M_0 slope of 3.5.

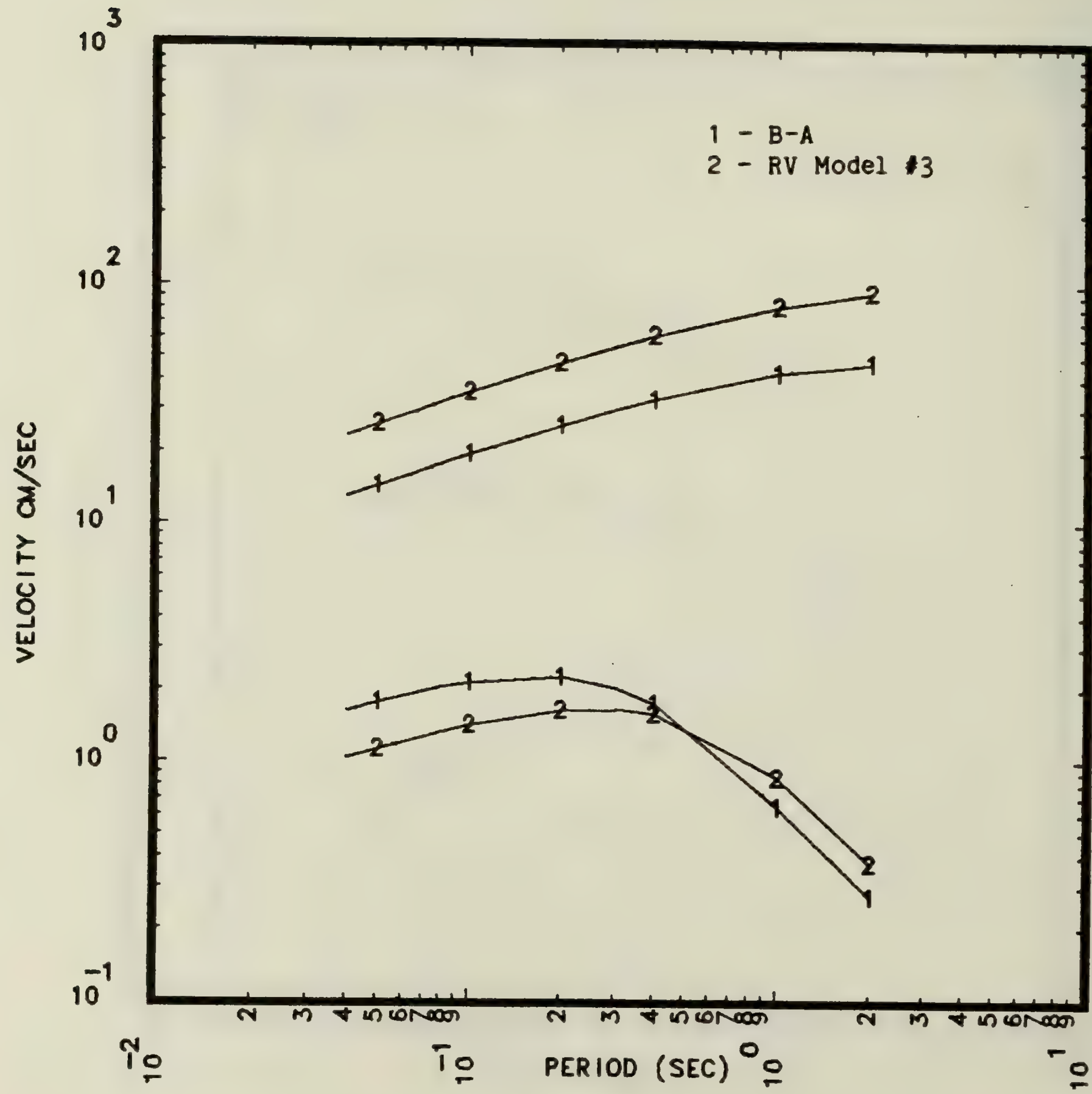


Figure 4.3.9 Comparison between the B-A 5% damped relative velocity spectral model and RV Model #3 for m_{Lg} = 5, 6 and 7 at an epicentral distance of 10 km.

4.4 Comparisons Between Models

In examining the comparisons made in this section, you should keep in mind how uncertainty is being modeled in our analysis. The GM models and associated weights that you select represent your modeling uncertainty, i.e., your uncertainty in the median estimates for the GM for any M-R value, the value assigned to the random vibration models the variation in the GM due to source and travel path effects.

Because there are a large number of candidate models that all differ to some degree, the question naturally arises as to which differences are significant? What is significant depends upon a number of factors which vary from site to site and from S-Expert to S-Expert. Overall, we generally found that differences between GM models in the 0 to 50 km range were more significant than for larger distances. We found that smaller earthquakes, e.g., in the range of 3.75 to 5, generally contribute from 25 to 50 percent of the hazard. We also found that typically a change of a factor of 2 in the probability of exceedance only corresponds to approximately a 30 percent increase in the PGA. Or conversely a factor of 2 in PGA leads to a factor of 8 in probability of exceedance. Thus two GM curves only slightly different can lead to hazard curves which are noticeably different.

In selecting models one often asks - how well does the model fit the data? Unfortunately, given the dispersion of the data there can be considerable differences between models that "fit" the data. This is illustrated in Fig. 4.4.1 where we compare Veneziano's direct model to the B-A and T-M models at $m_{Lg} = 5$. All three of the models "fitted" the data, yet as can be seen from Fig. 4.4.1, there are significant differences between these models.

As indicated in Section 4.1, a large number of intensity based models can be developed. Comparisons between a number of such models are given in Bernreuter et al. Here it is of some interest to compare Veneziano's new combined intensity based model to the intensity based model most heavily

weighted by the GM Panel at the end of our first feedback in 1984. In particular the model consists of the modified Gupta-Nuttli intensity attenuation model combined with the Trifunac (1976) relation between PGA and site intensity. The original Gupta-Nuttli intensity attenuation was modified by reducing the leading constant by 0.5 to correct for the fact that the Gupta-Nuttli relation was based on isoseismals rather than individual intensity reports and, for the reasons discussed in Section 5, 0.5 units to approximately correct the relation to give I (R, I_0) for rock sites. The comparison between the two models is shown in Fig. 4.4.2. Given the very different origins of the two models they are in reasonable agreement except at small and large epicentral distances.

In Fig. 4.4.3, Veneziano's direct model is compared to Nuttli's (1986) semi-empirical model for the case of f_c-M_0 slope of 4. These two models are in relative agreement, however, the attenuation with distance is somewhat different between the two models.

There is a significant difference between Veneziano's models and the constant stress drop model, e.g., the B-A version, as shown in Fig. 4.4.4.

As indicated in Section 4.3, one can obtain a wide range for the estimate of GM from the RV model by selecting the parameters for Eq. 4.3.10 and the approach used to obtain the M_0-m_{Lg} relation. For example, in Fig. 4.4.5 we give a comparison between Veneziano's direct model and model 3 introducted in Section 4.3 which incorporates a M_0-f_c slope of 3.5 and Nuttli's empirical M_0-m_{Lg} relation. Clearly, by adjustment of the constant c in Eq. 4.3.10, one could put the two models in "better" agreement. Certainly, it would be hard to reject either model on the basis of the existing ENA strong GM data. However, as pointed out in Section 4.3, model 3 appears to result in a model which has unrealistically strong scaling of the GM with magnitude. On the other hand, the constant stress drop model (f_c-M_0 slope of 3) may result in a model which scales too weakly with magnitude.

The RV model leads to a spectral shape significantly different from the spectral shape of the intensity based models. This is illustrated in Fig. 4.4.6 where a rock version of the Trifunac-Lee spectral model (Trifunac and Lee's relation between I_s, S_v, and site type, and the Gupta-Nuttli attenuation of I_s with R modified was discussed earlier in this section) is compared to the B-A RV model for m_{Lg} = 5, 6 and 7 at an epicentral distance of 10 km. As one might expect, relative to the RV model the intensity based model has more long period energy and less short period energy. We would expect the Trifunac -Lee model to have more long period energy than a "direct" model because a site can experience the same intensity I_s at larger distances from a large magnitude earthquake than from a smaller magnitude earthquake. The Trifunac-Lee model does not include terms in the relation between I_s and S_v to account for the fact that we would expect more long period motion from larger more distant events than smaller nearby events. Both the SEP-1 and SEP-2 models include terms to account for the correlation and, as can be seen by comparing Figs. 4.1.2 to 4.1.3 and 4.1.4, that the longer period energy content is reduced in these models relative to the Trifunac-Lee or the Trifunac-Anderson model. However, it is still evident that both the SEP-1 and SEP-2 models have more long period energy than the RV model. It should be noted that the spectral models in Figs. 4.1.2, 3 and 4 are soil models and the RV model is a rock model. However, even if a correction for site conditions is applied, the same basic conclusion holds.

Also shown in Fig. 4.4.6 are the estimates for S_v at 0.1 and 1.0 sec. from Veneziano's direct model for the same magnitudes. Although Veneziano's model leads to significantly higher values for S_v than either B-A's or T-M's models, the shape seems to agree with the RV model. This naturally leads to the question: Is the spectral content of ENA earthquakes different than WUS earthquakes? Certainly, the little existing data might lead one to this conclusion as is illustrated by Figs. 4.4.7a and b. In Fig. 4.4.7a we compare a typical WUS spectral shape (obtained from the recording in Golden Gate Park from the Daly City earthquake) to the spectral shape of the record for the New Brunswick earthquake recorded at Mitchell Lake Road. In Fig. 4.4.7b we

compare the Golden Gate spectral shape to that obtained from the record at the downstream station at Franklin Falls Dam from the New Hampshire earthquake. We see--relatively speaking--that the spectral content of the ENA records is similar to the spectral content of the RV model while the spectral content of the WUS record is similar to the intensity based model. Limited comparisons are questionable given the variability between earthquakes. For example, the one other near-field recording of an ENA earthquake looks more like a typical WUS earthquake as is shown in Fig. 4.4.8.

It is of some interest to compare the RV spectral model to empirical predictions. In Fig. 4.4.9, we compare a constant stress drop RV model ($\Delta\sigma$ = 100 bars) with f_{max} = 15 hz to the median spectral estimate at rock sites computed using the WUS empirical model developed by Joyner and Boore (1982) for moment magnitudes of 5, 6 and 7 at an epicentral distance of 15 km. A depth of 10 km was used for the RV model. The comparison is reasonably good; however, the RV model does not have enough energy in the 2-10 hz range. Also, the f_{max} filter does not match the data too well. The main change in the B-A or the T-M model for ENA is changing f_{max} from about 15 hz to 40 to 50 hz and the introducting of a scaling between M_0 and m_{Lg}. The scaling between M_0-m_{Lg} is an important consideration as is illustrated in Fig. 4.4.10 where we compare the WUS Joyner-Boore model for magnitudes of 5, 6 and 7 to the predictions of the B-A ENA model for m_{Lg} = 5, 6 and 7. In the WUS, it is generally assumed that M_L and moment magnitude (below saturation of the M_L scale) are the same. Herrmann and Nuttli have argued that at least around magnitude 5, m_{Lg} = M_L. If this is the case, then we see from Fig. 4.4.10 that scaling between M_0-m_{Lg} used by B-A may result in a model which underestimates the spectral intensity for a given magnitude earthquake. Also shown in Fig. 4.4.10 are the estimated values for S_V = 0.1 and 1.0 sec. based on Veneziano's direct model. Unfortunately, Veneziano's model does not shed much light on any difference in the relative frequency content in the 2 to 10 hz range between WUS and ENA earthquakes.

In Fig. 4.4.11 we compare, at an epicenter distance of 10 km for m_{Lg} 5, 6 and 7, the B-A model to an RV model with a M_0-f_c slope of 3.5 with the constant c in Eq. 4.3.10 adjusted so that the model would give approximately the same S_v values as the B-A model at $m_{Lg} = 5$. The Nuttli empirical relation between M_0 and m_{Lg} was used to convert m_{Lg} to M_0. Also shown in Fig. 4.4.11 are the estimates from Veneziano's direct model.

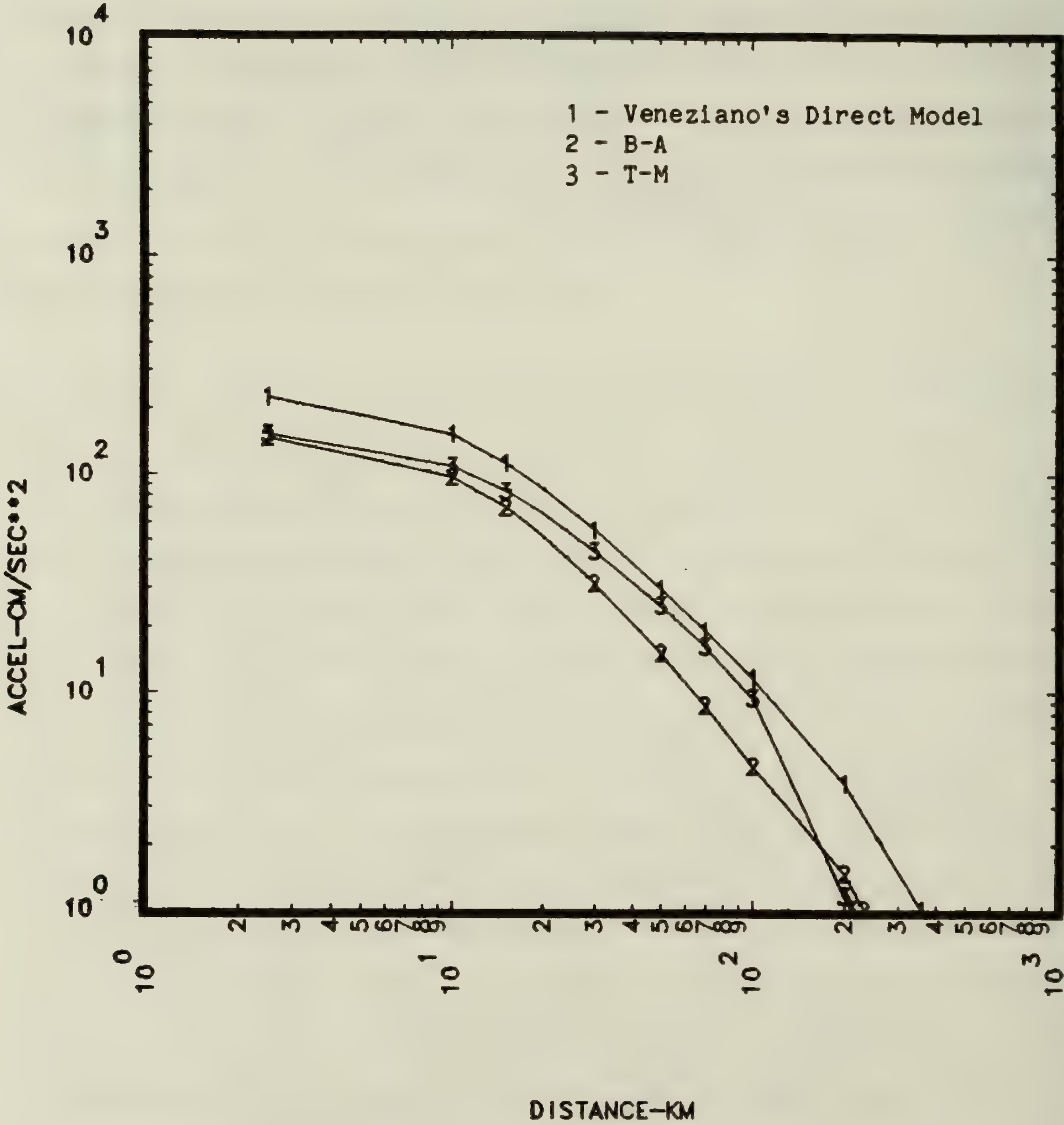


Figure 4.4.1 Comparison between Veneziano's direct PGA model, the B-A PGA model, and the T-M PGA model for $m_{Lg} = 5$.

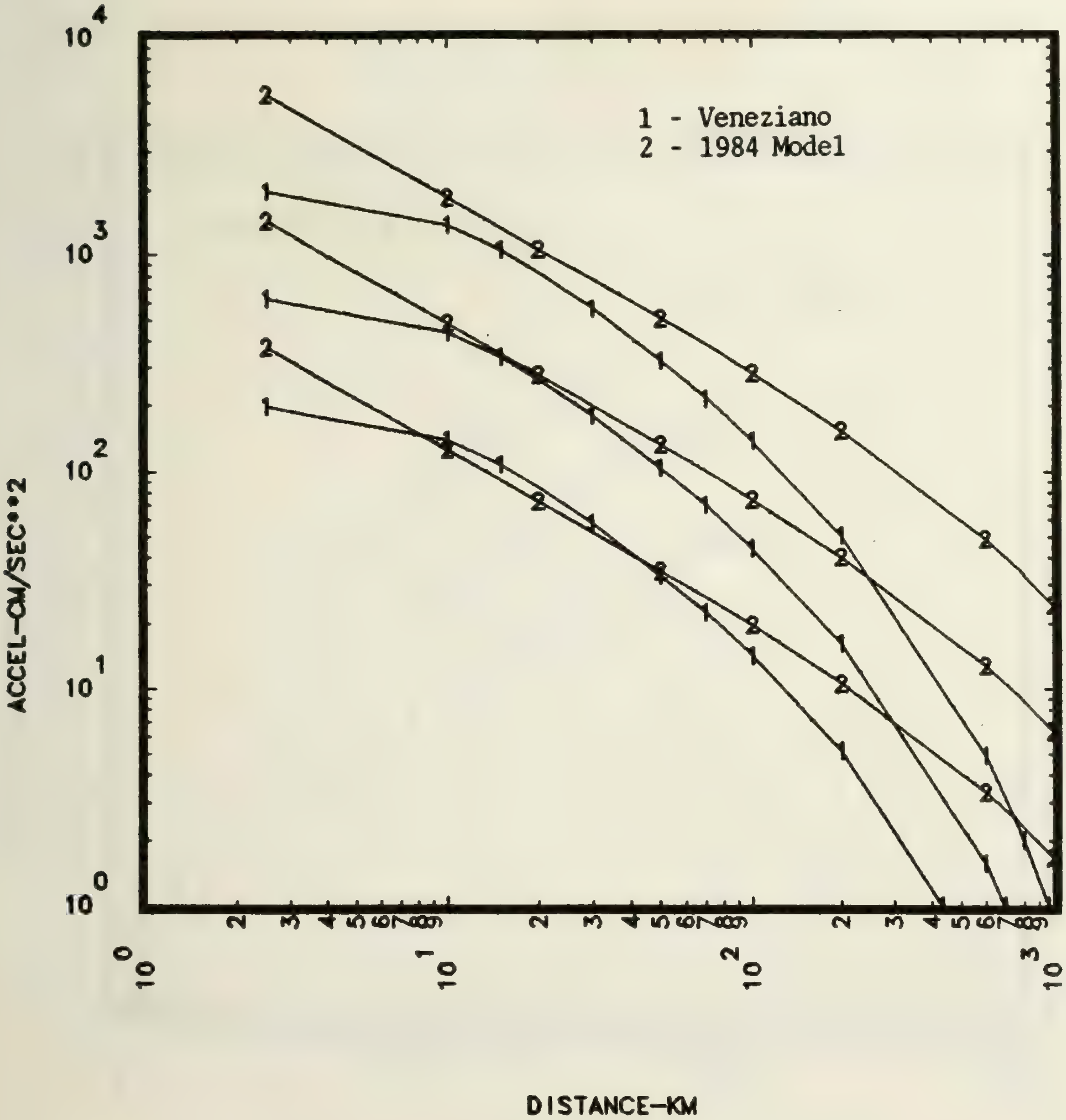


Figure 4.4.2 Comparison between Veneziano's combined intensity based PGA model and the intensity based model most heavily weighted at the end of our feedback in 1984 for m_{Lg} = 5, 6 and 7 at rock sites. The 1984 model has been modified as described in the text to account for site conditions.

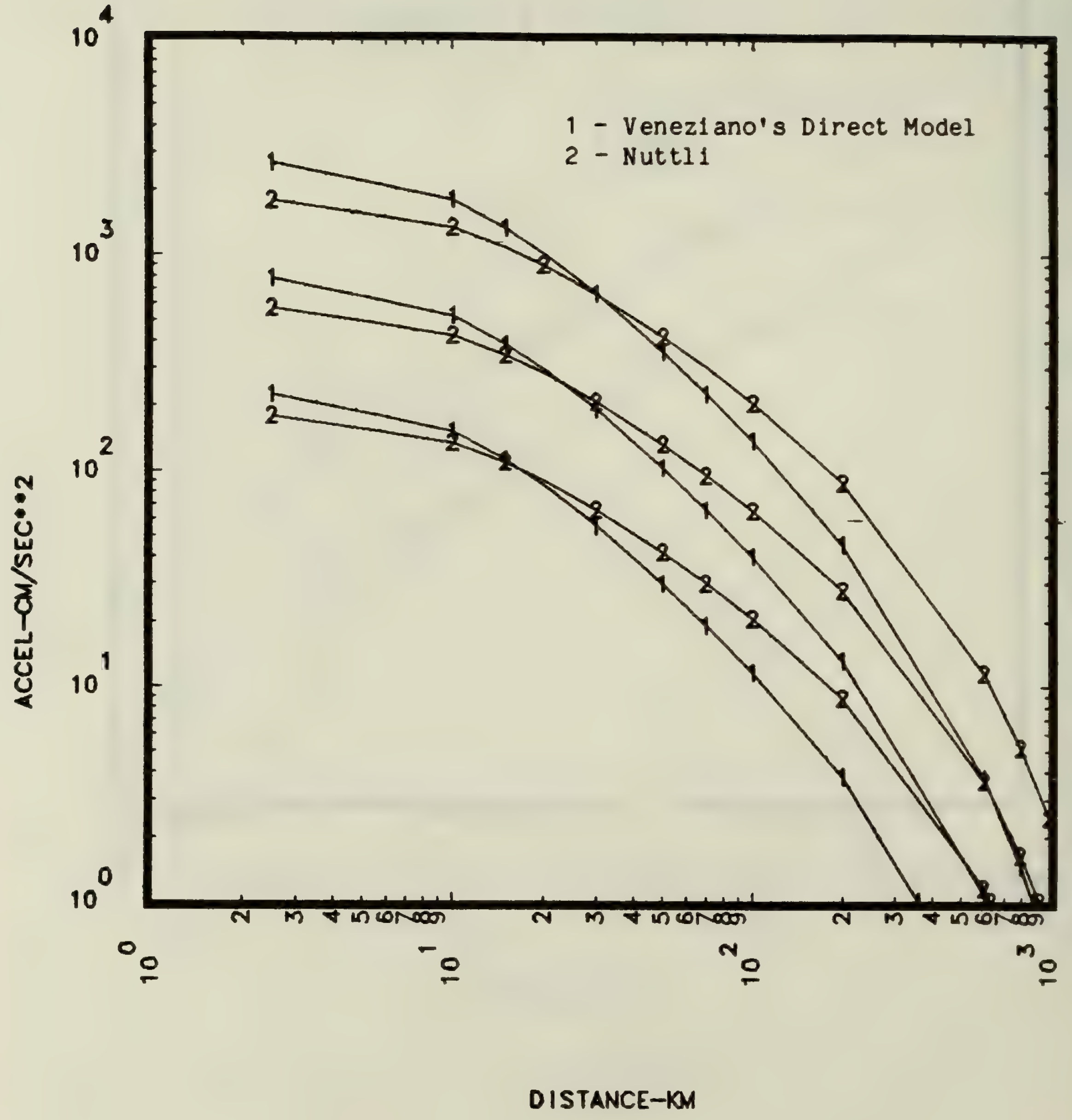


Figure 4.4.3 Comparison between Veneziano's direct PGA model and Nuttli's (1986) PGA model based on a M_0-f_c slope of 4 for m_{Lg} = 5, 6 and 7.

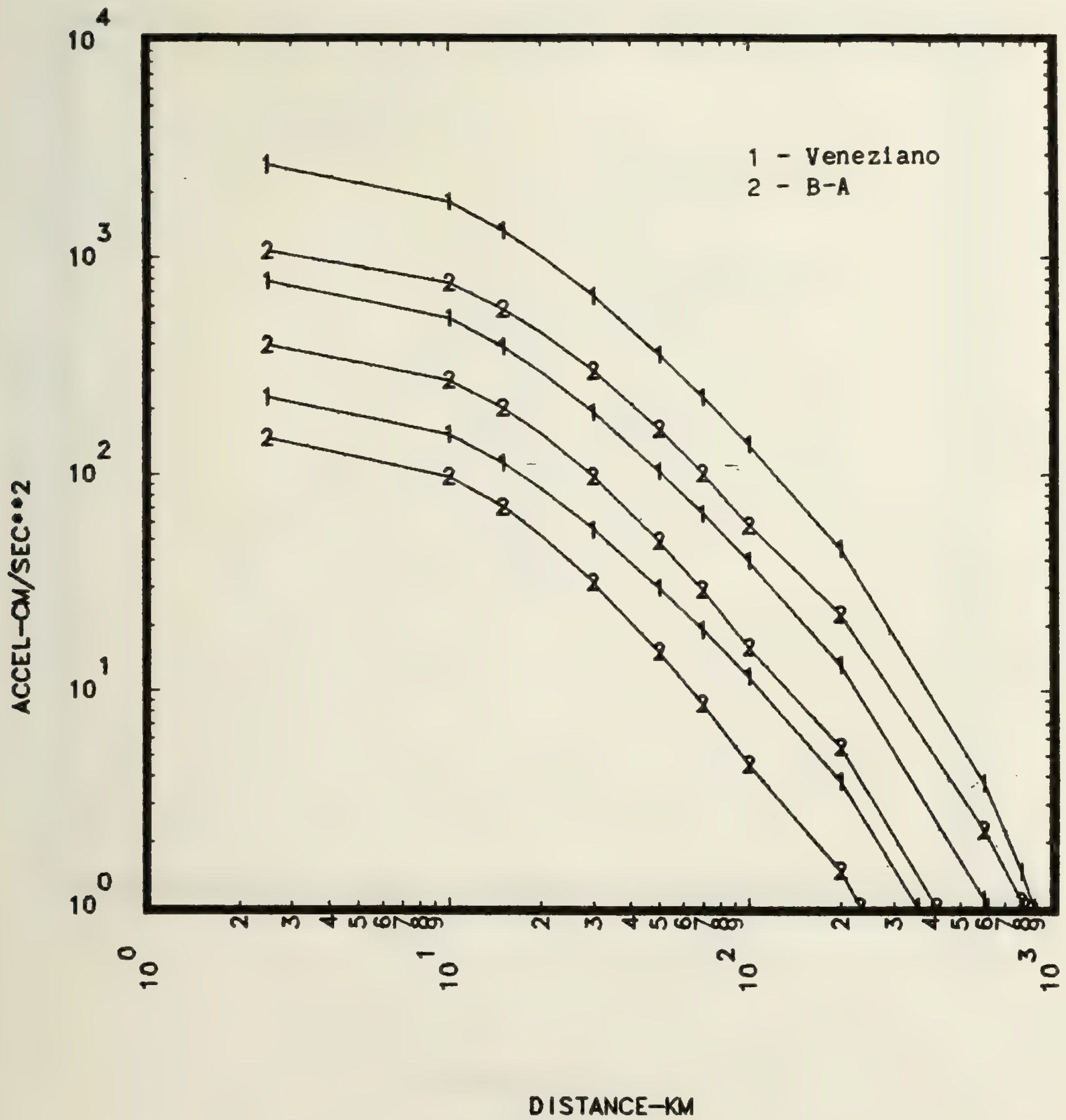


Figure 4.4.4 Comparison between Veneziano's direct PGA model and the B-A model for m_{Lg} = 5, 6 and 7.

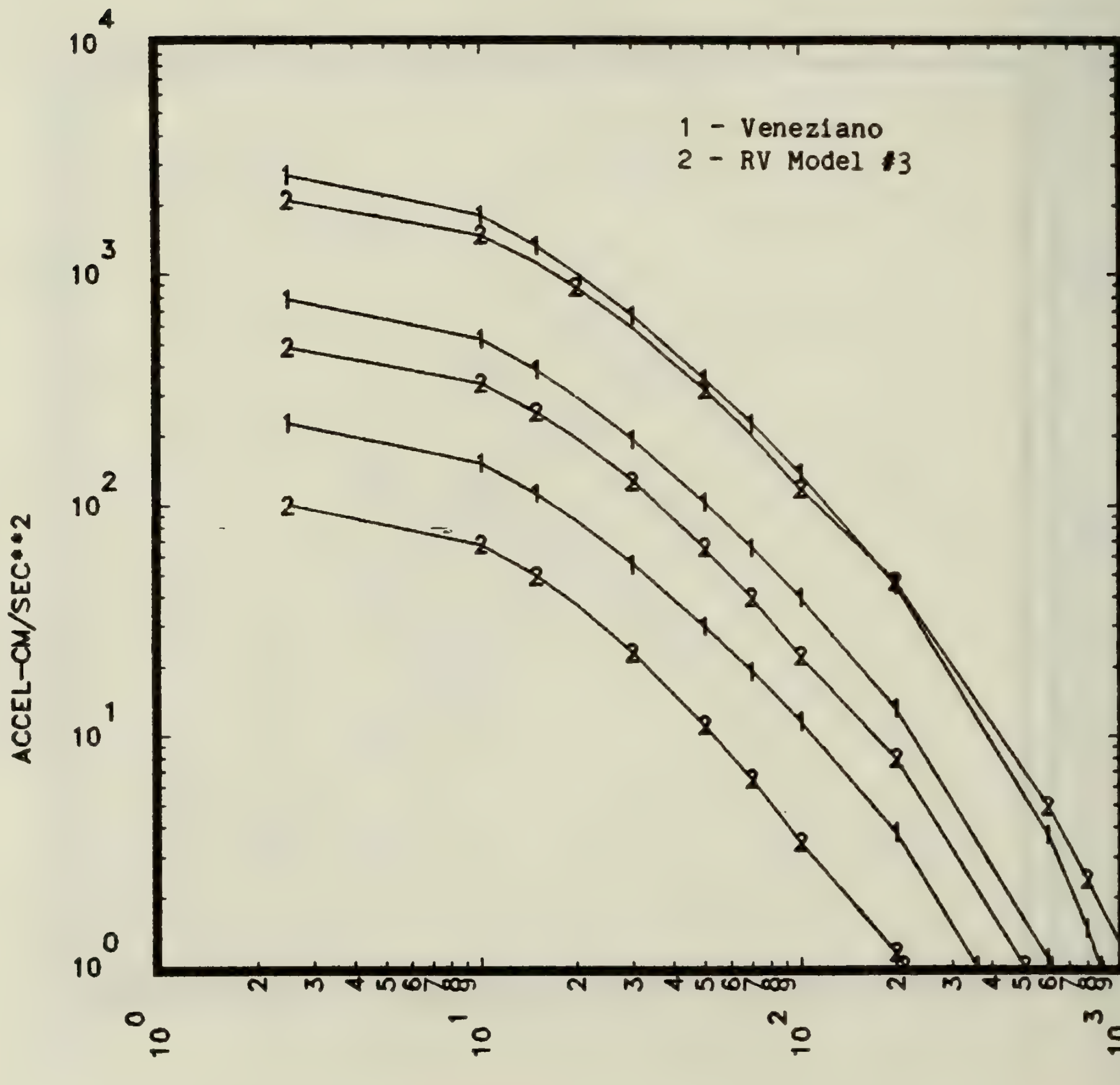


Figure 4.4.5 Comparison between Veneziano's direct PGA model and the RV model #3 for m_{Lg} = 5, 6 and 7

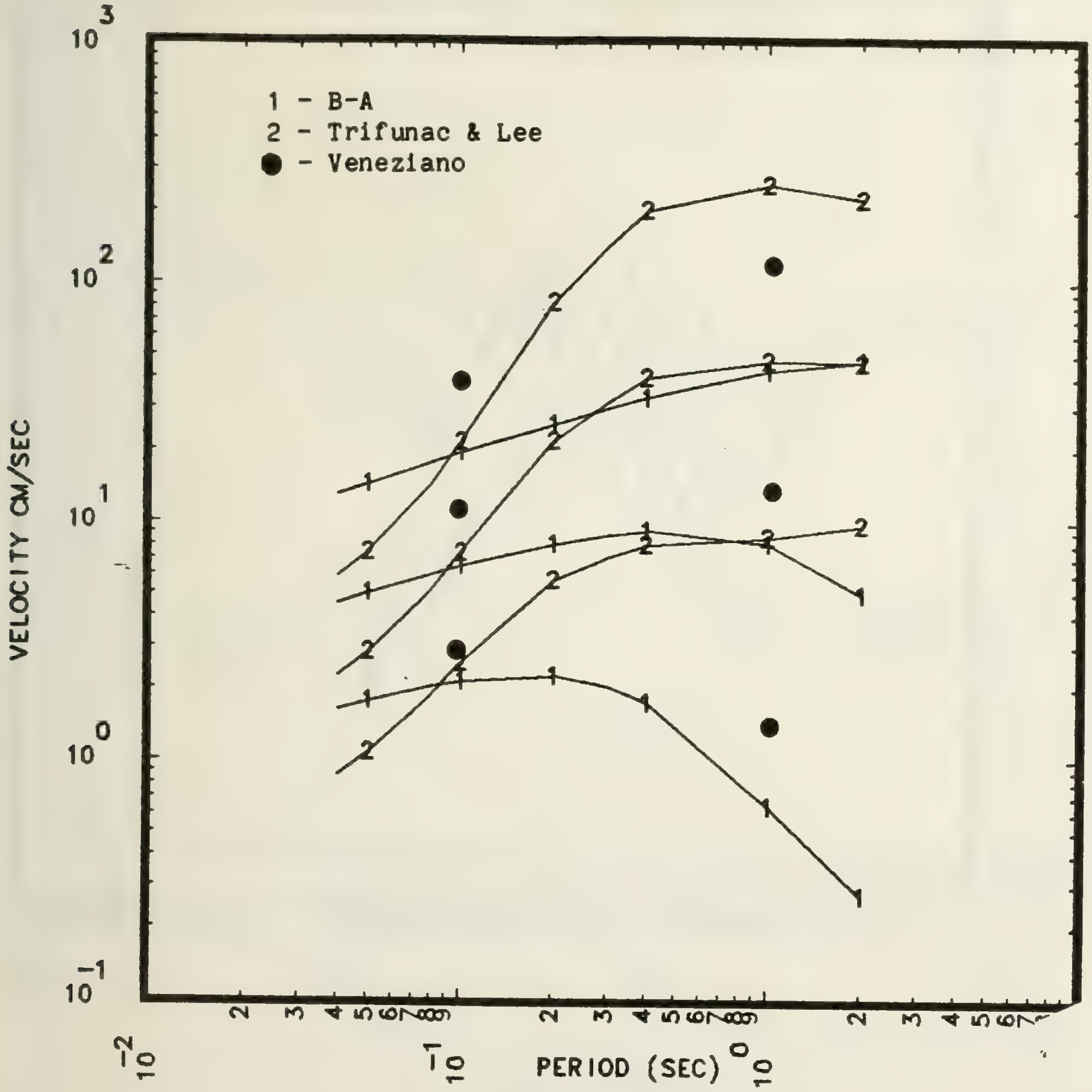


Figure 4.4.6 Comparison between the B-A 5% damped relative velocity spectral model and the intensity based spectral model based on Trifunac and Lee's relation between site intensity and S_v for m_{Lg} = 5, 6 and 7 at an epicentral distance of 10 km. Also shown are the spectral estimates from Veneziano's direct model.

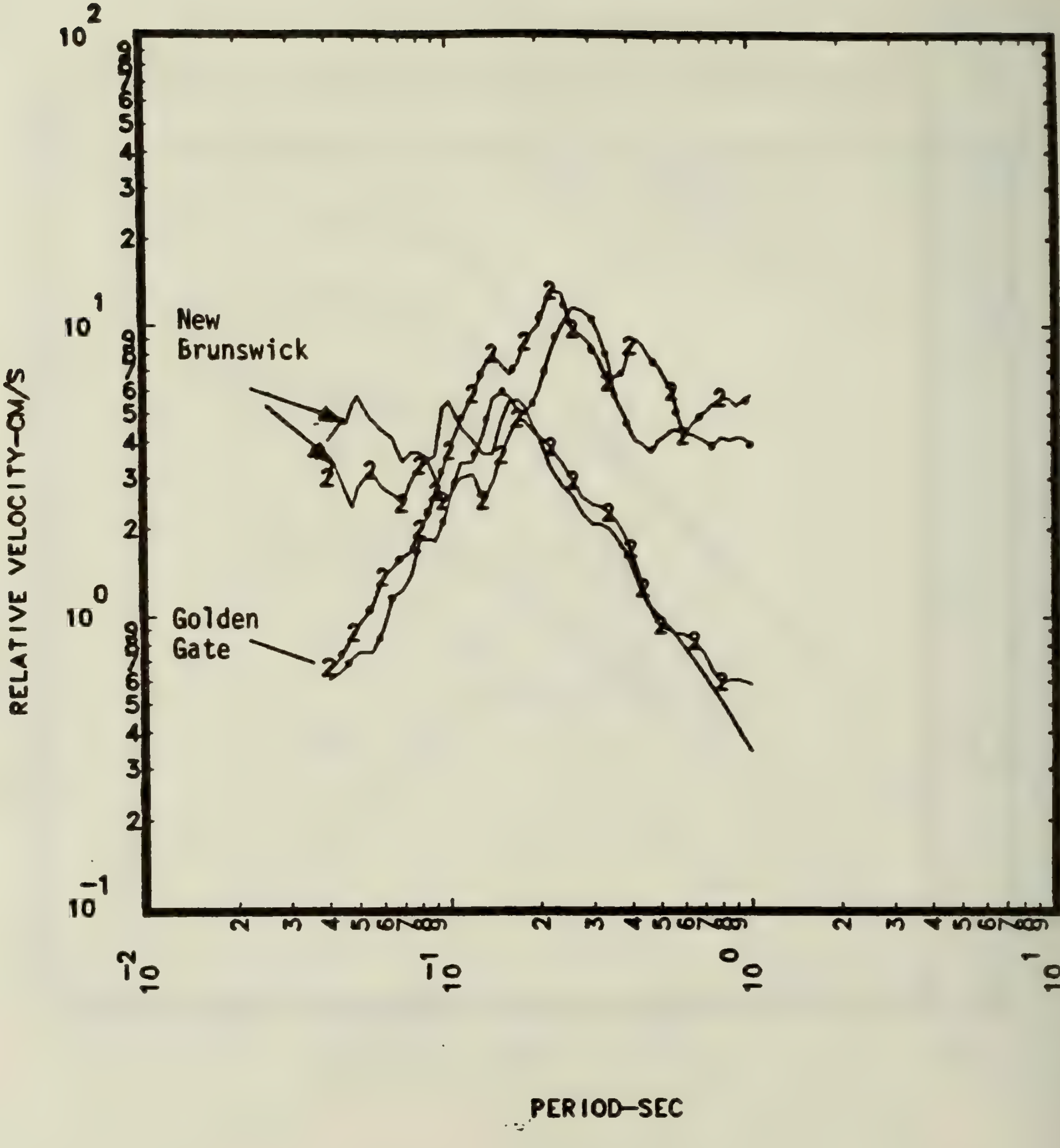


Figure 4.4.7a Comparison of the 5% damped relative velocity spectra for both horizontal components for the New Brunswick earthquake recorded at Mitchell Lake Road and the Daly City earthquake recorded at Golden Gate Park.

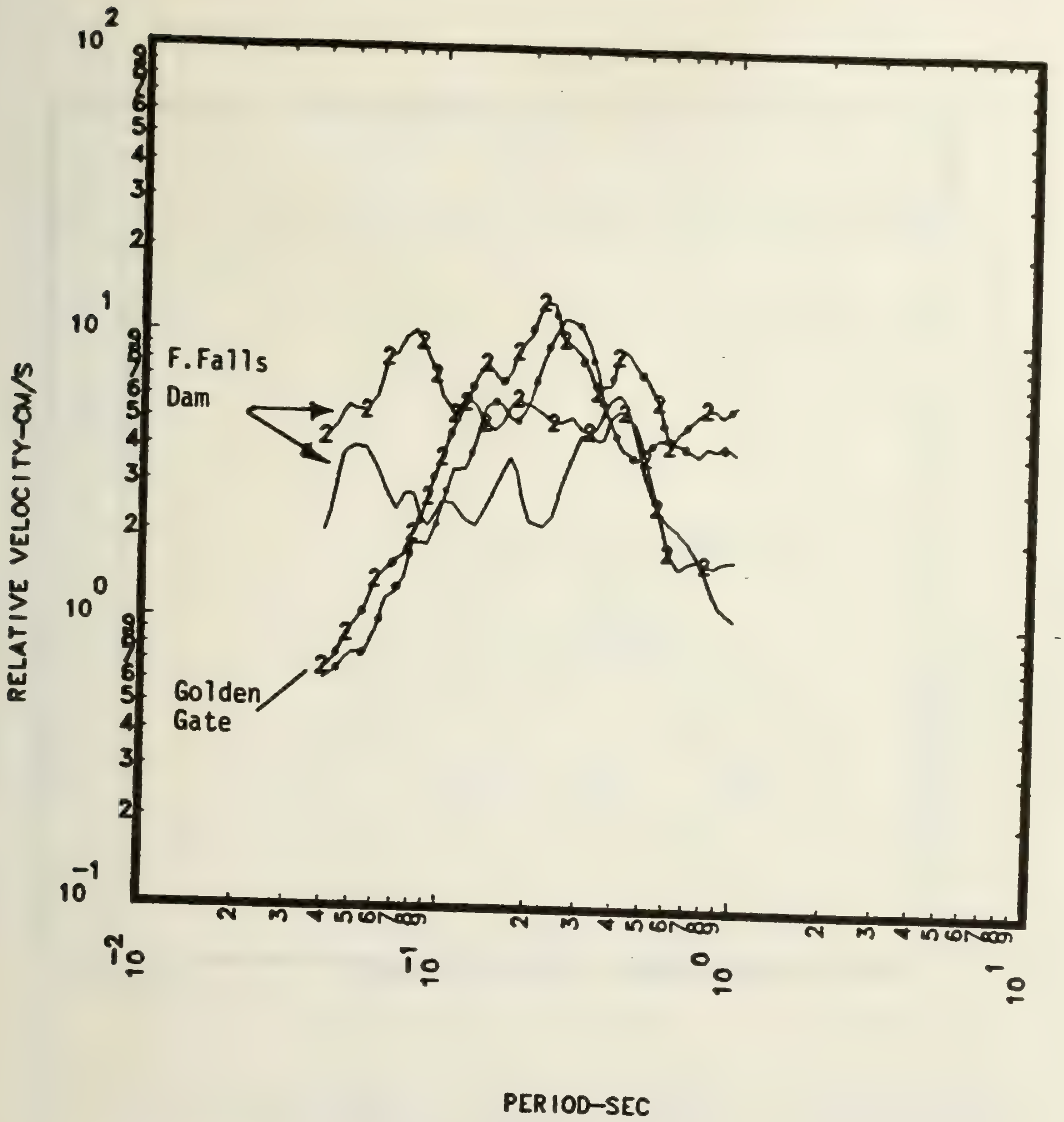


Figure 4.4.7b Comparison of the 5% damped relative velocity spectra for both horizontal components for the New Hampshire earthquake recorded at the downstream station at Franklin Falls Dam and the Daly City earthquake recorded at Golden Gate Park.

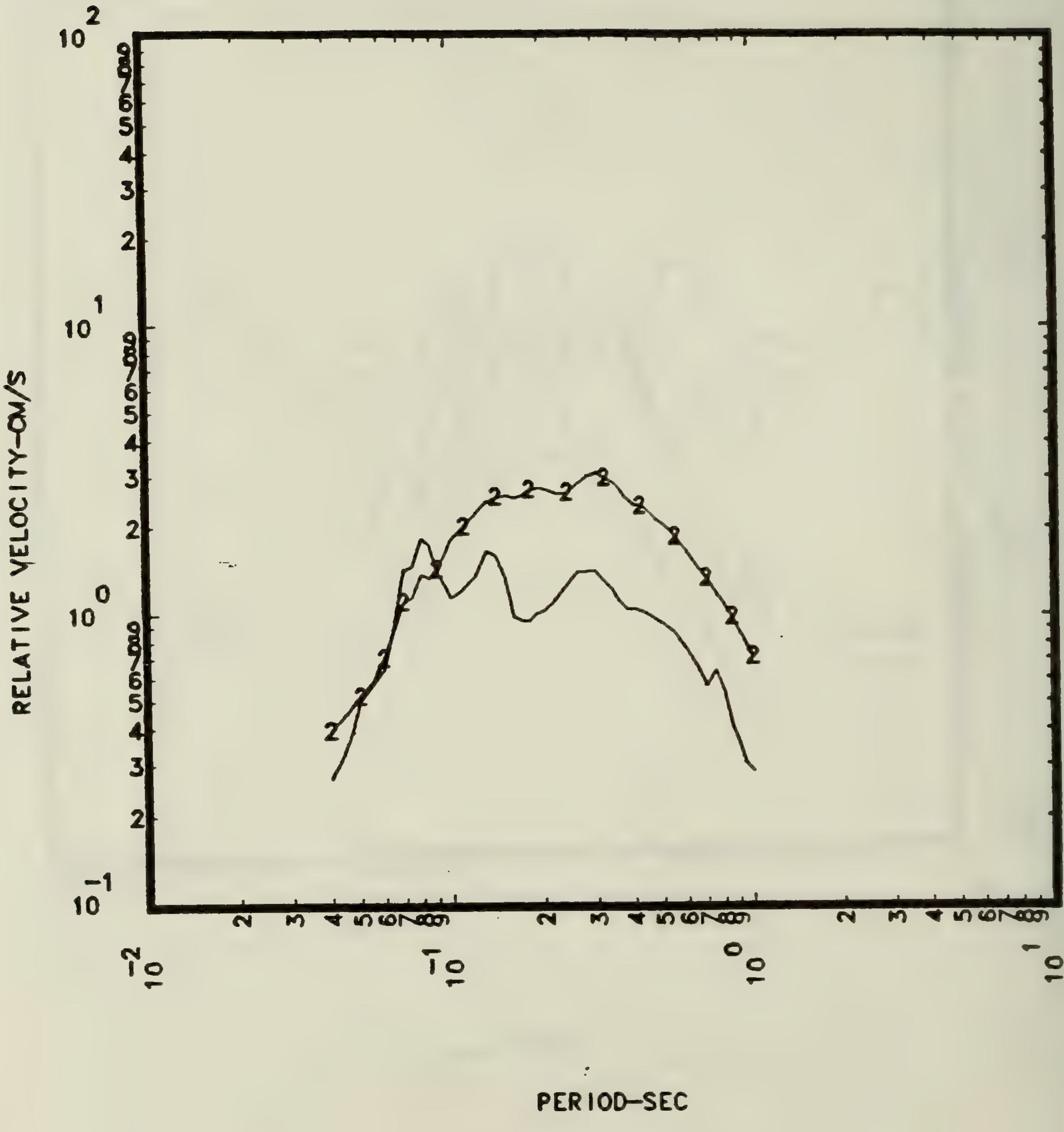


Figure 4.4.8 5% damped relative velocity spectra of both horizontal components for the magnitude 4.25 June 13, 1975 earthquake recorded at New Madrid.

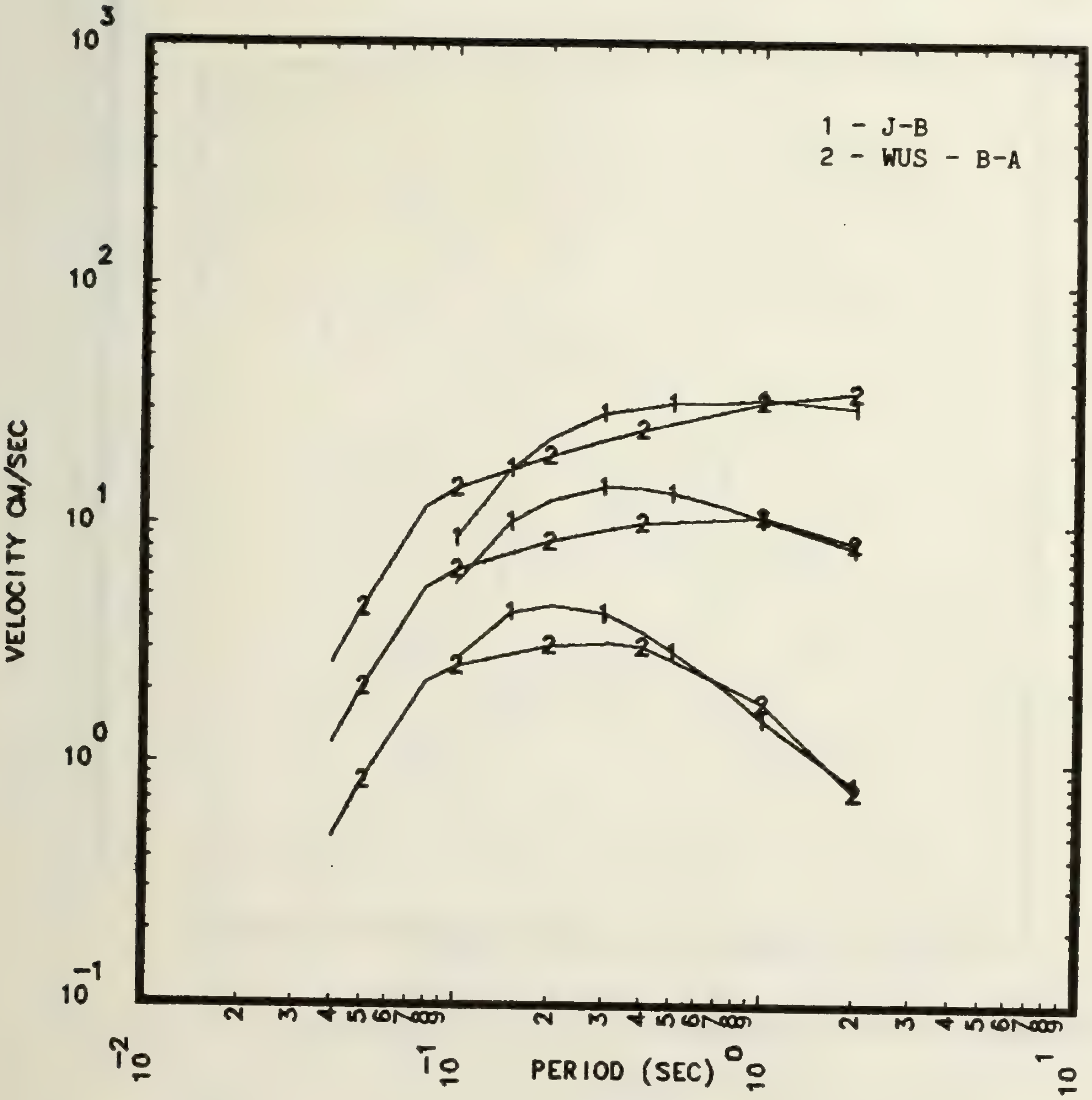


Figure 4.4.9 Comparison between the empirical Joyner-Boore (1982) WUS 5% damped relative velocity spectral model and a WUS version of the B-A RV model for moment magnitudes of 5, 6 and 7 at an epicentral distance of 15 km.

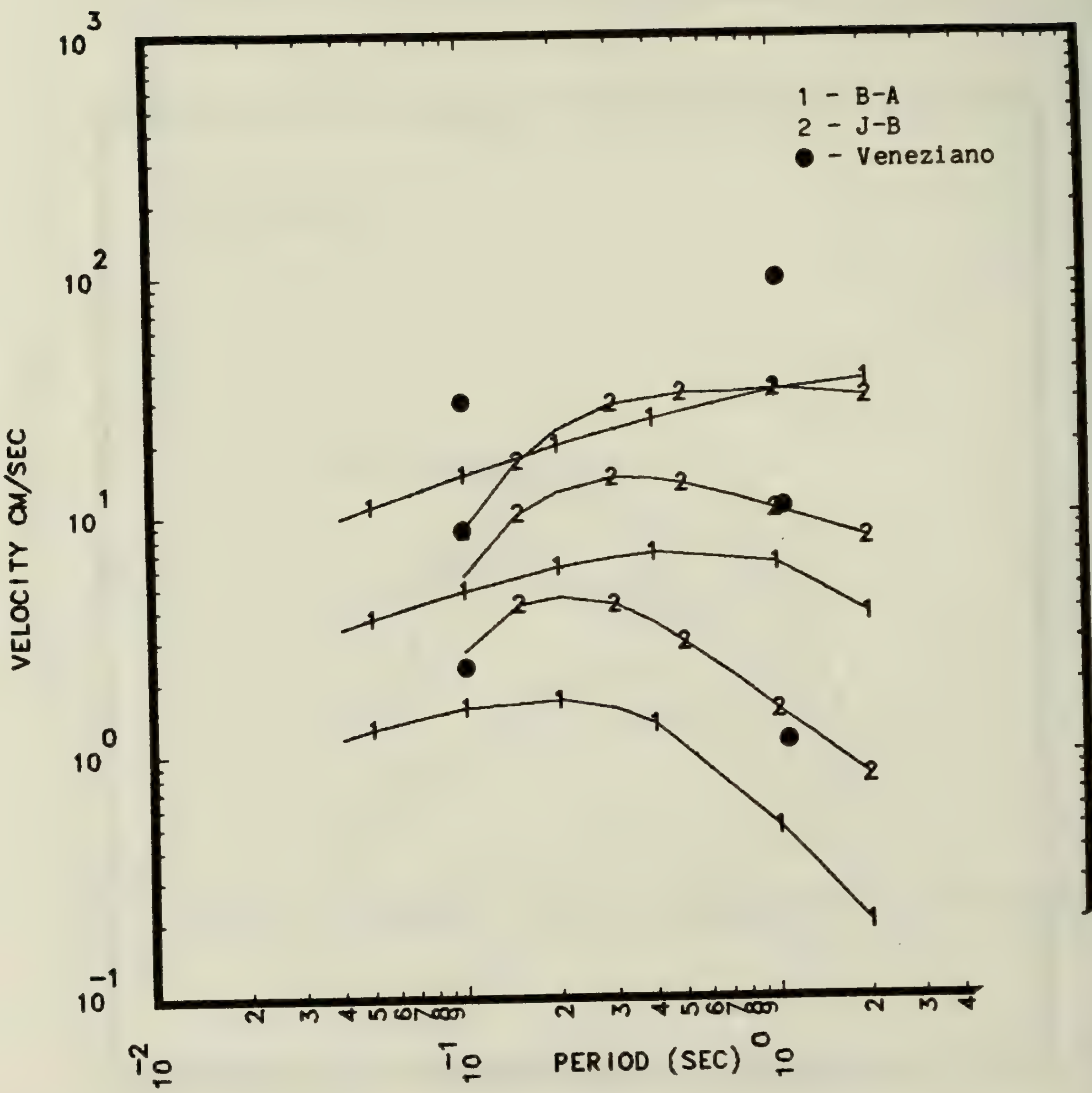


Figure 4.4.10 Comparison between the empirical Joyner-Boore (1982) 5% damped relative velocity spectral model and the B-A model at an epicentral distance of 15 km for m_{Lg} = 5, 6 and 7. It was assumed that $M_L = m_{Lg}$ to relate the J-B model to the B-A model. Also plotted are the estimates from Veneziano's direct model.

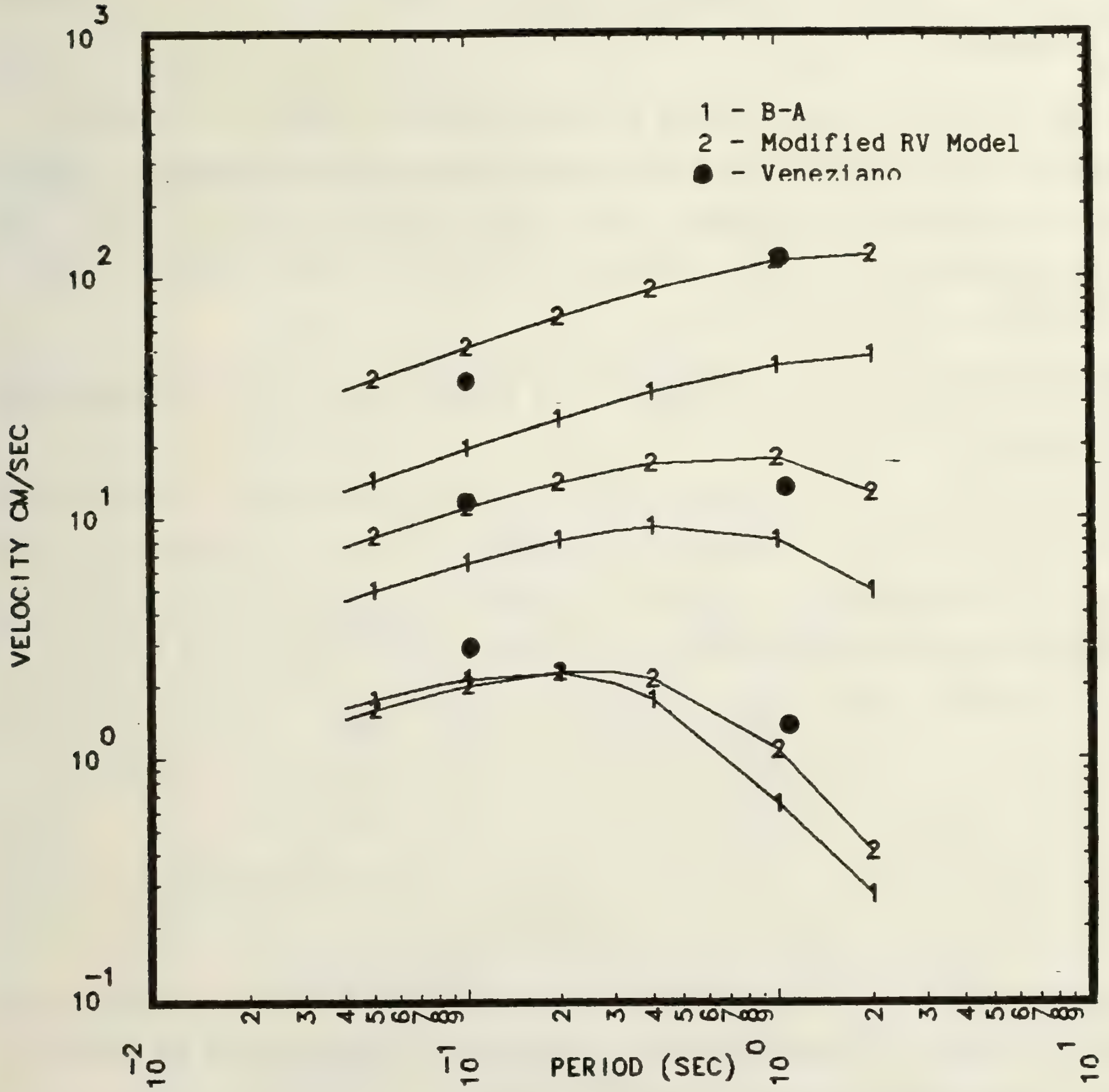


Figure 4.4.11 Comparison between the B-A 5% damped relative velocity spectral model and a modified version of RV Model #3 for m_{Lg} = 5, 6 and 7 at an epicentral distance of 10 km. Also shown are the estimates from Veneziano's direct model.

5 MODELING SITE EFFECTS

5.1 Approach

At our two day workshop we only briefly touched on local site effects. However, at our June 23, 1986 meeting we reviewed in some detail our approach and the basis for our approach. Our overall approach has not changed from that discussed in our first feedback questionnaire to you (see Bernreuter et al. (1985) pp E5-1 to E5-55).

Basically, in our approach each site is placed in one of the following eight categories:

Rock

Sand-like	Till-like
S-1	T-1
S-2	T-2
S-3	T-3

Deep Soil

Each GM model is assumed to be developed for either a rock or generic soil case. This is a slight departure from the development given in Bernreuter et al. (1985) where the base case was assumed to be deep soil sites. In actual fact it is generally a mixture of deep soil sites along with data from a few shallow soil and rock sites. Thus, as discussed at the June meeting, we have defined a new generic case (base case) which does not fit any site category and use the deep soil as a category with correction factors different from one.

Based on the analysis of several "typical" data sets, we assume that the generic soil base case is made up of the following:

- o rock-like sites - 17%

- o relatively shallow soil - 22%

- o deep soil - 61%

We explain later how our assumed makeup of the base core soil is used in our analysis.

As explained at the workshop, we use a Monte Carlo approach to perform the uncertainty analysis. For each trial we draw randomly (relative to the weights provided) one of the GM models, then draw (relative to the weights provided) one of three possible correction approaches to correct the selected GM model from its base case to the category that the site falls into. The three correction approaches incorporated in our methodology are:

1. No correction applied

2. Apply a simple correction, either the site is soil or rock.

3. Apply our categorical correction approach

The no correction approach requires no discussion. The simple correction approach is a bit more complex. Any specific GM model is assumed to be either a rock or a soil model. If the site's category is the same as the base case of the GM model then no correction is applied. If not, then a simple constant correction factor is applied. Figure 5.1 shows several typical "simple" corection factors.

The case is more complicated when the categorical correction approach is used. As discussed at the June meeting and in Bernreuter et al. (1985) on E5-1 to E-55 a set of correction factors were developed in the following manner. Figures 5.2 and 5.3 illustrate our procedure. To get a set of time histories to use in the analysis, we selected a set of 20 time histories recorded at rock sites with various magnitudes and distances to incorporate the uncertainty from the source and travel path effects in the analysis. The site response was calculated by assuming one-dimensional vertically propagating SH waves. Sites were modeled as a system of horizontal layers of infinite extent. Viscoelastic material properties for each layer were assumed for the shear modulus, density, Poisson's ratio, and material damping. The input was one of 20 rock outcrop time histories. The site response for each of the S1, S2, S3, T1, T2, T3 and deep soil categories was computed using the SHAKE Program.

To account for uncertainties in material properties and earthquake characteristics, we performed repeated deterministic analyses, each analysis simulating an earthquake occurrence. By performing many such analyses and by varying the values of the input parameters, a mean response and it's coefficient of variation was obtained. Variability in the seismic input is included by sampling from the twenty time histories to obtain a different earthquake time history for each simulation. Variability in the dynamic modeling was introduced by sampling sets of input parameters (mainly shear wave velocities of soil and rock, damping ratio of soil and the depth of soil deposit) from assumed probability distributions for each simulation. A lognormal distribution for each input parameter was assumed for this study.

Using the above data we developed two median correction factors as a function of spectral frequency (to correct the GM model from rock to the site's category or from generic soil to the site's category) and the uncertainty in our estimate of the median in the following manner. For the rock base case, we simply computed the correction factor by taking the ratio of the computed spectrum at the top of each soil column to the input rock spectrum. For each

category this resulted in a set of twenty correction factors. It was assumed that a lognormal distribution could be used to model the uncertainty in the estimated correction factor. Figure 5.4a shows the resultant median corection factors for the sand-like categories relative to rock, and Fig. 5.4b shows them for the till-like sites relative to rock.

It is more difficult to obtain the correction factors to correct GM models whose base case is considered to be a generic soil. In this case for any given site category, eight correction factors were generated for each time history by dividing the computed spectrum at the top of the soil column for the category of interest by each of the other computed spectra (including itself). Once again a lognormal model was assumed to model the uncertainty in the correction factors for each site category. The median correction factor was then generated by a weighted average where the weights were taken to model the assumed makeup of site types making up the generic soil case. Figure 5.5a shows the resultant median correction factors for sand-like categories relative to generic soil and Fig. 5.5b shows them for till-like categories relative to generic soil.

In the Monte Carlo uncertainty analysis when the categorical correction approach is selected the correction factor is simulated based on the assumed lognormal distribution for the particular category, with the median and the standard deviation derived for that distribution.

5.2 Base Cases for Various GM Models

It would seem that it should not be a difficult task to determine what the base case is for each GM model, as each model is developed using a given data set and/or some theoretical model which should establish the base case. In actual application, it is not quite so simple. For example, it is generally argued that the RV models represent rock sites. This is primarily because the value chosen for f_m is consistent with rock. In addition, a smoothed spectral shape is used which should be more consistent with hardrock than soil. These

conjectures have not been verified. In fact, it is almost impossible to verify these conjectures given the large variability between earthquakes and because we have little data recorded at hard rock sites.

Both Nuttli's and Campbell's models, discussed in Section 4.2, should be classified as generic soil models as they are based primarily on data recorded at soil sites, however, data recorded at rock and shallower soil sites were also included.

The intensity based models present a problem. It seems a reasonable to argue that most of the data making up the intensity reports were at soil sites, thus the relations giving the attenuation of I_S should be consider primarily a soil relation...but it includes rock and shallow soil sites also.

It is our opinion that the process of developing an intensity based model with rock as the base case by combining a relation of the form

$$I_S = F(I_0, R) \qquad (5.1)$$

with

$$GM = G(I_S, I_0, R, S) \qquad (5.2)$$

where S = site type variable

should not be employed because the relation (5.1) is primarily for soil sites. It is generally agreed (based on small amounts of data) that at a given epicentral distance the intensity at rock sites is lower than at soil sites. For example, Lee and Trifunac (1985), using the WUS strong motion data set, found that at the same distance I_S at rock sites is on the average about 1/2 units lower than at soil sites. On the other hand investigators, e.g., Trifunac and Brady (1975) and Murphy and O'Brien (1977) found that relations

of the form of eq. (5.2) indicated that the PGA at rock sites is about a factor of 1.5 to 2 higher than at soil sites for the same I_S. When relations of the form (5.1) are substituted into (5.2) to obtain a GM model including regional attenuation, i.e.

$$GM = G_1(I_0,R,S) \qquad (5.3)$$

one obtains a result that the PGA is significantly larger at rock sites than at soil sites for the same I_0 and R. This is in disagreement with more direct regression analysis results. The problem arises because in (5.1) one does not have the correction for site type. This is the point made in Appendix 2.

There are at least two possible approaches to overcome this problem. One approach is to take the ad hoc approach we used in Section 4.4 and estimate the correction needed to correct Eq. (5.1) for rock sites. In Section 4.4 we somewhat arbitrarily assumed that

$$(I_S)_{rock} = (I_S)_{generic} - 0.5 \qquad (5.4)$$

based on Lee and Trifunac's results. Another approach is the approach used by Veneziano in Appendix 2.

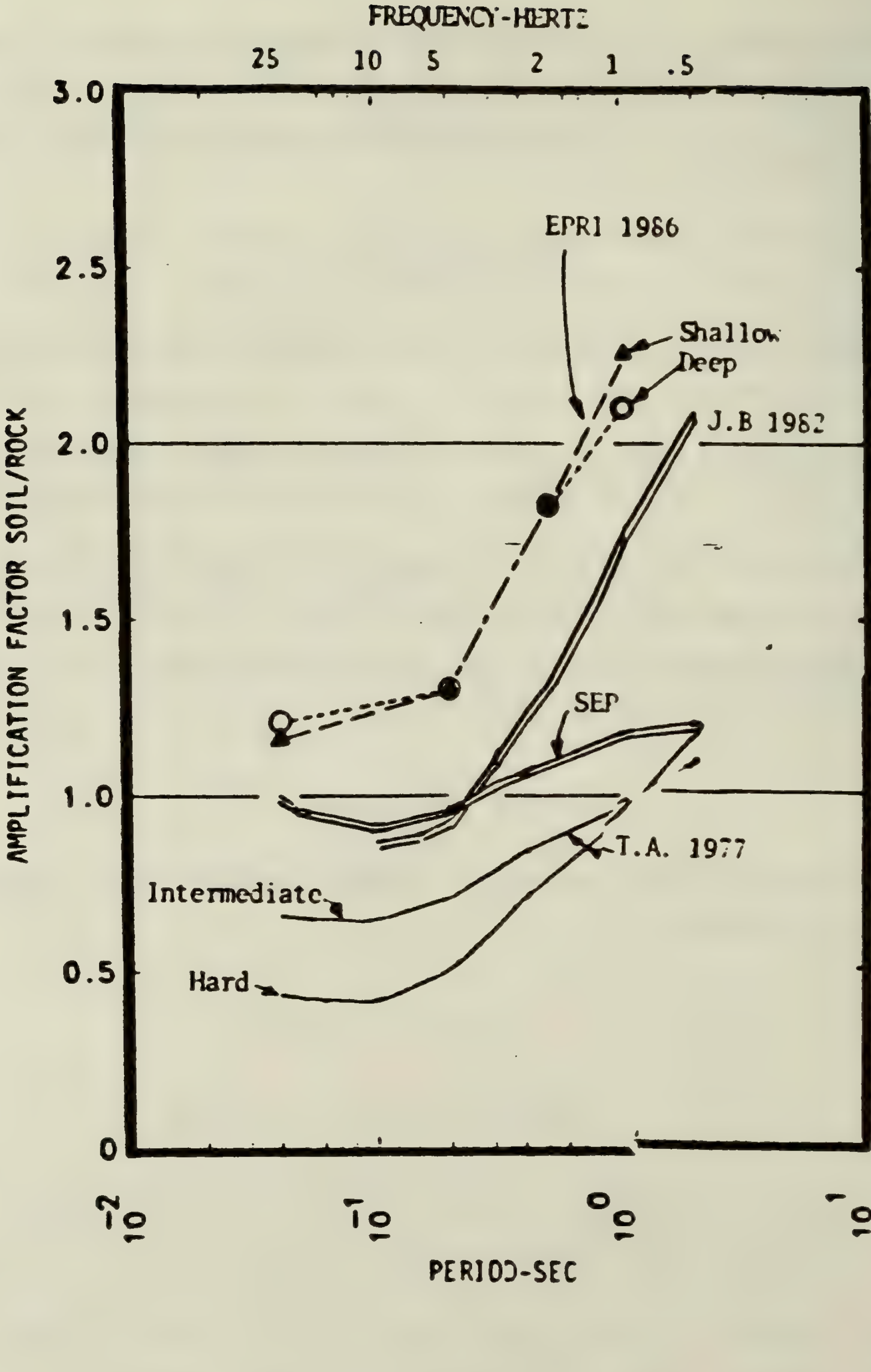


Figure 5.1 Simple correction factors relative to rock.

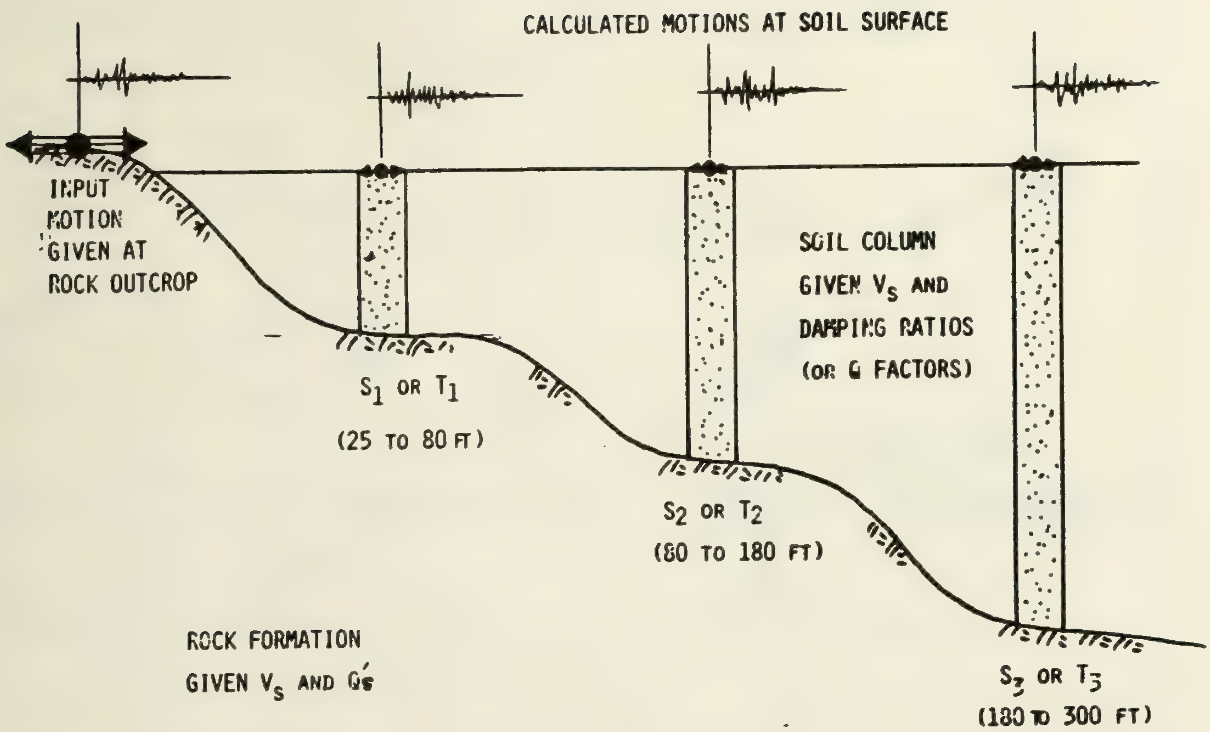


Figure 5.2 Schedmatic Representation of our Computation Procedures to Model the Site Correction Factors.

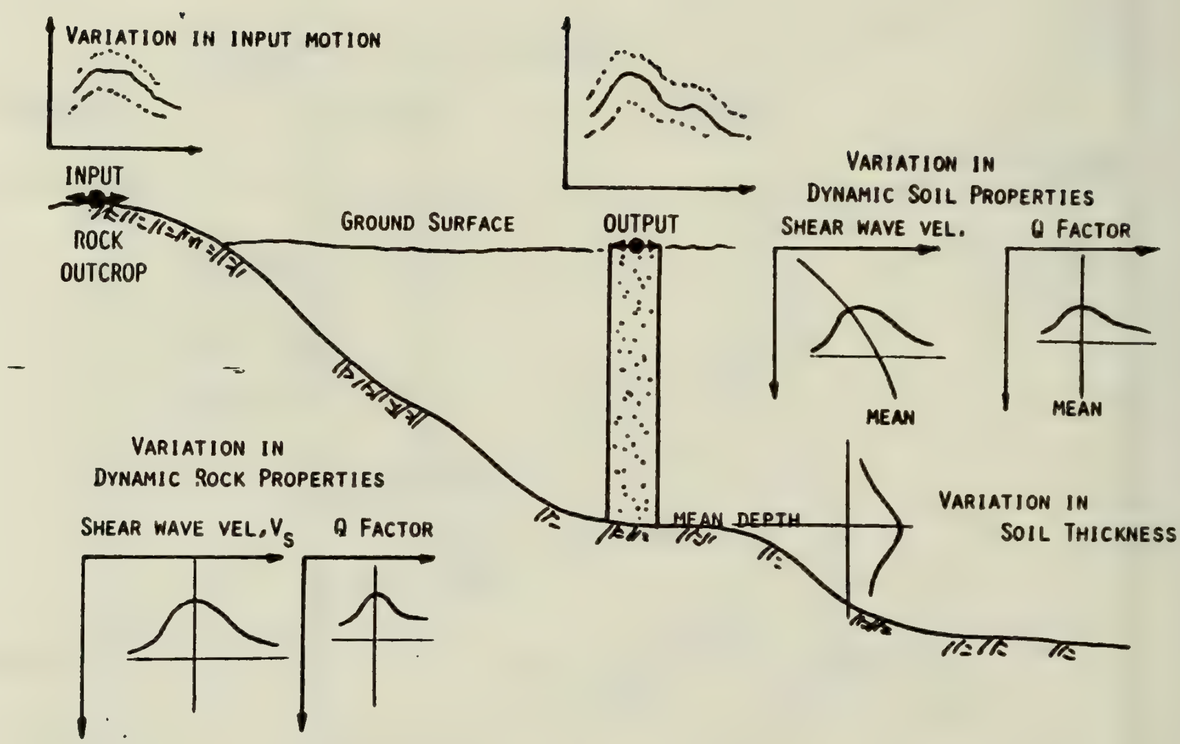


Figure 5.3 The physical parameters used in the 1-D model are drawn from probability distributions.

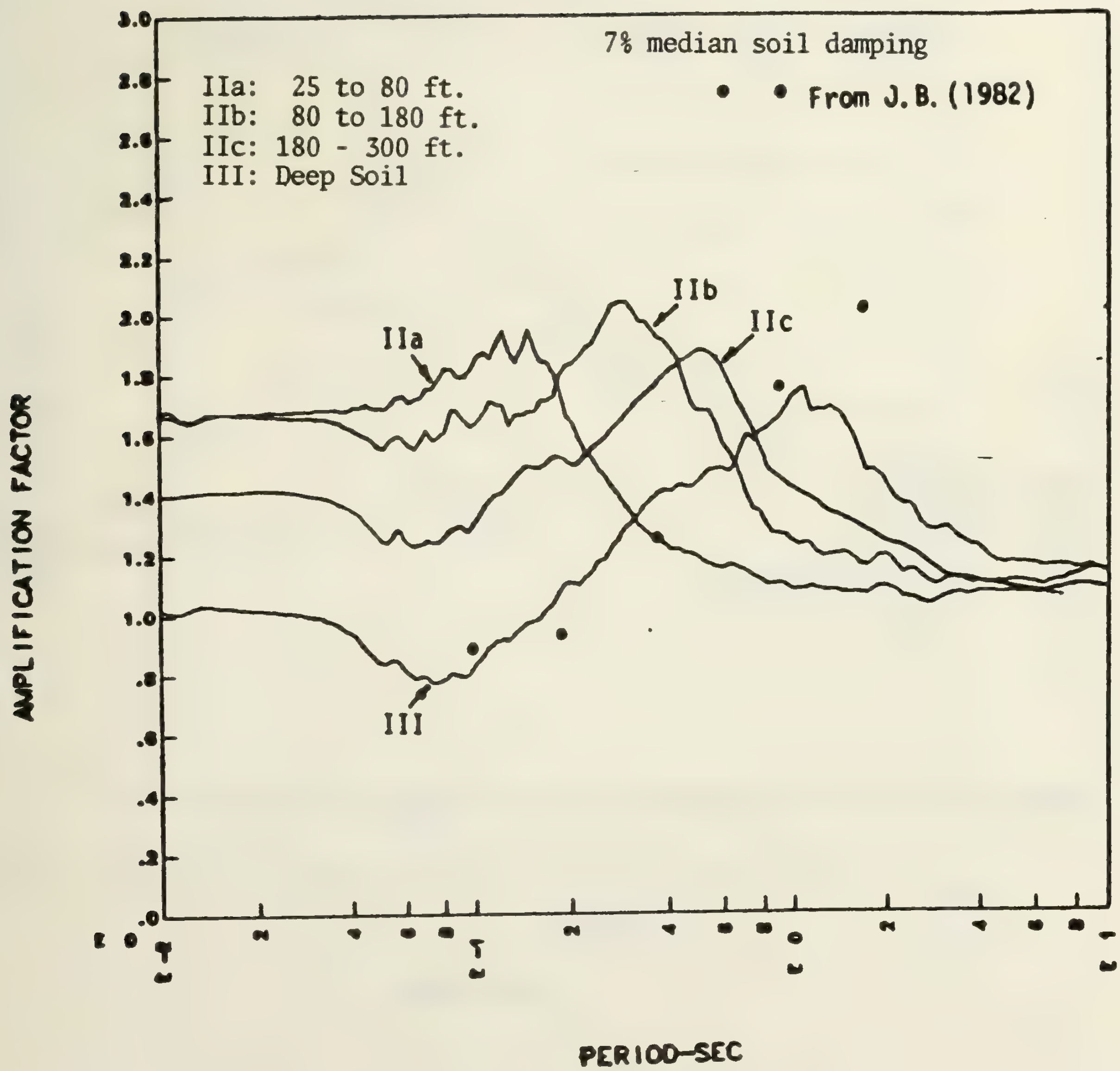


Figure 5.4a Median site correction factors relative to rock for sand-like categories.

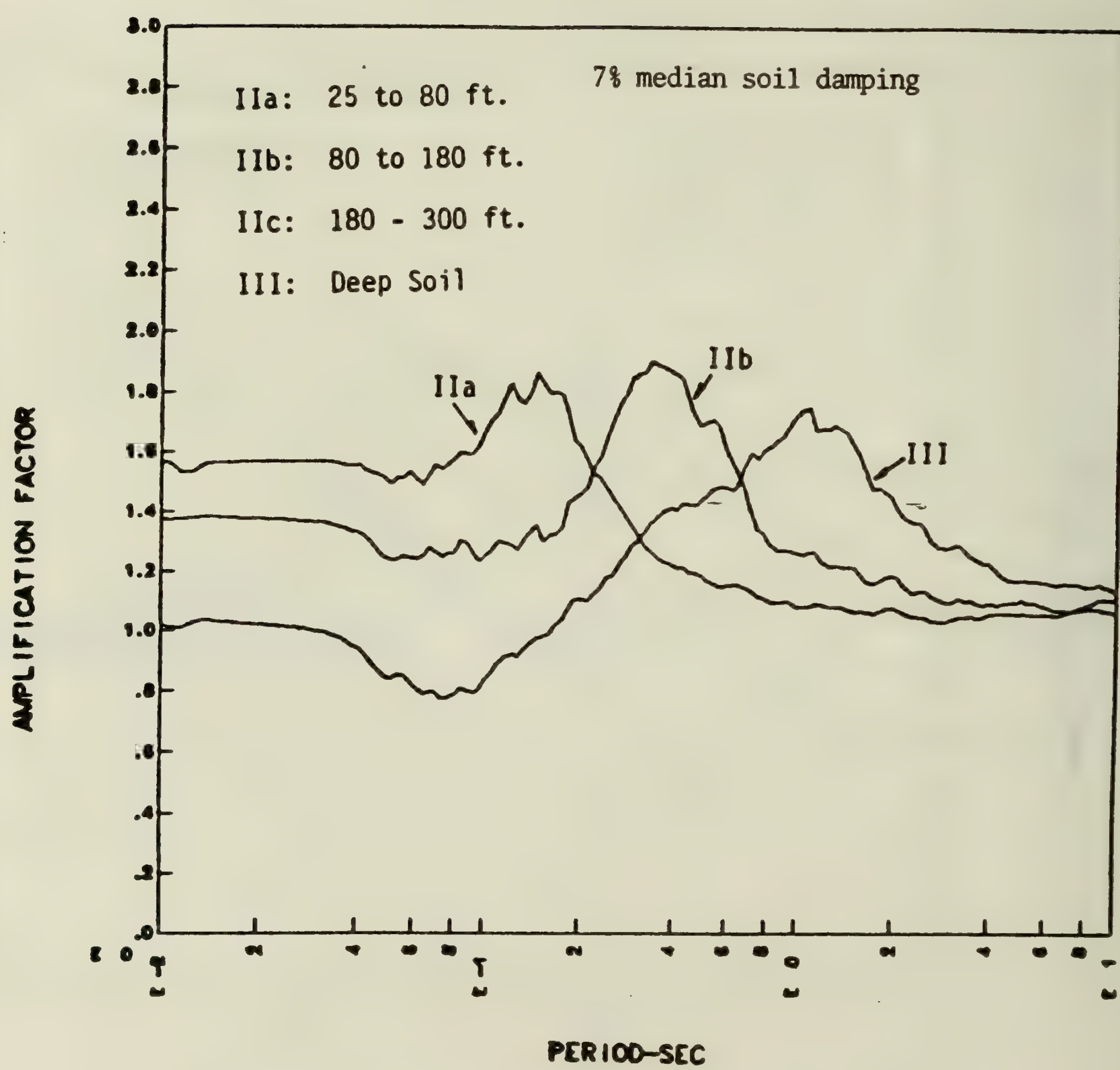


Figure 5.4b Median site correction factors relative to rock for till-like categories.

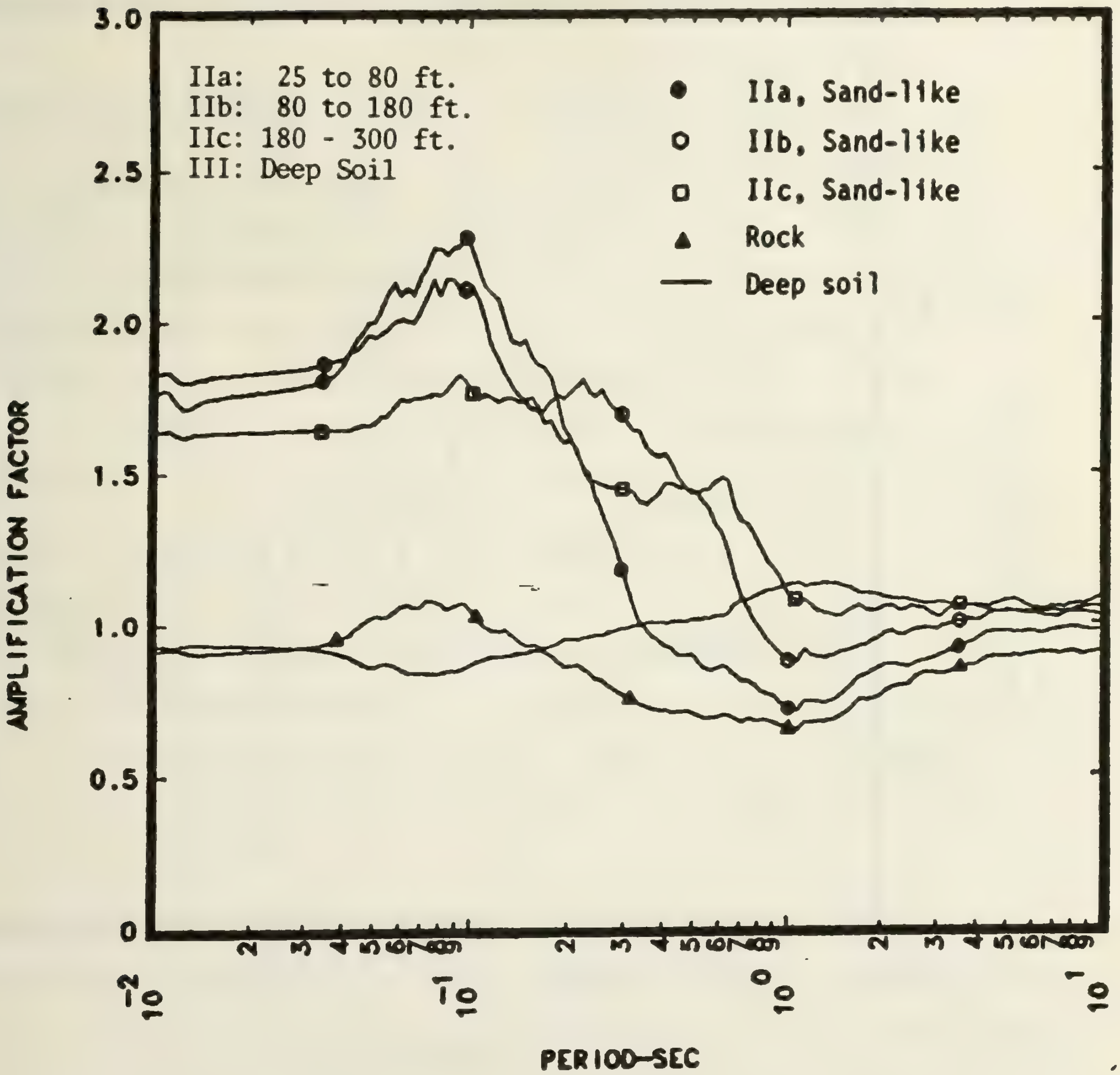


Figure 5.5a Median site correction factors for sand-like categories relative to generic soil base case.

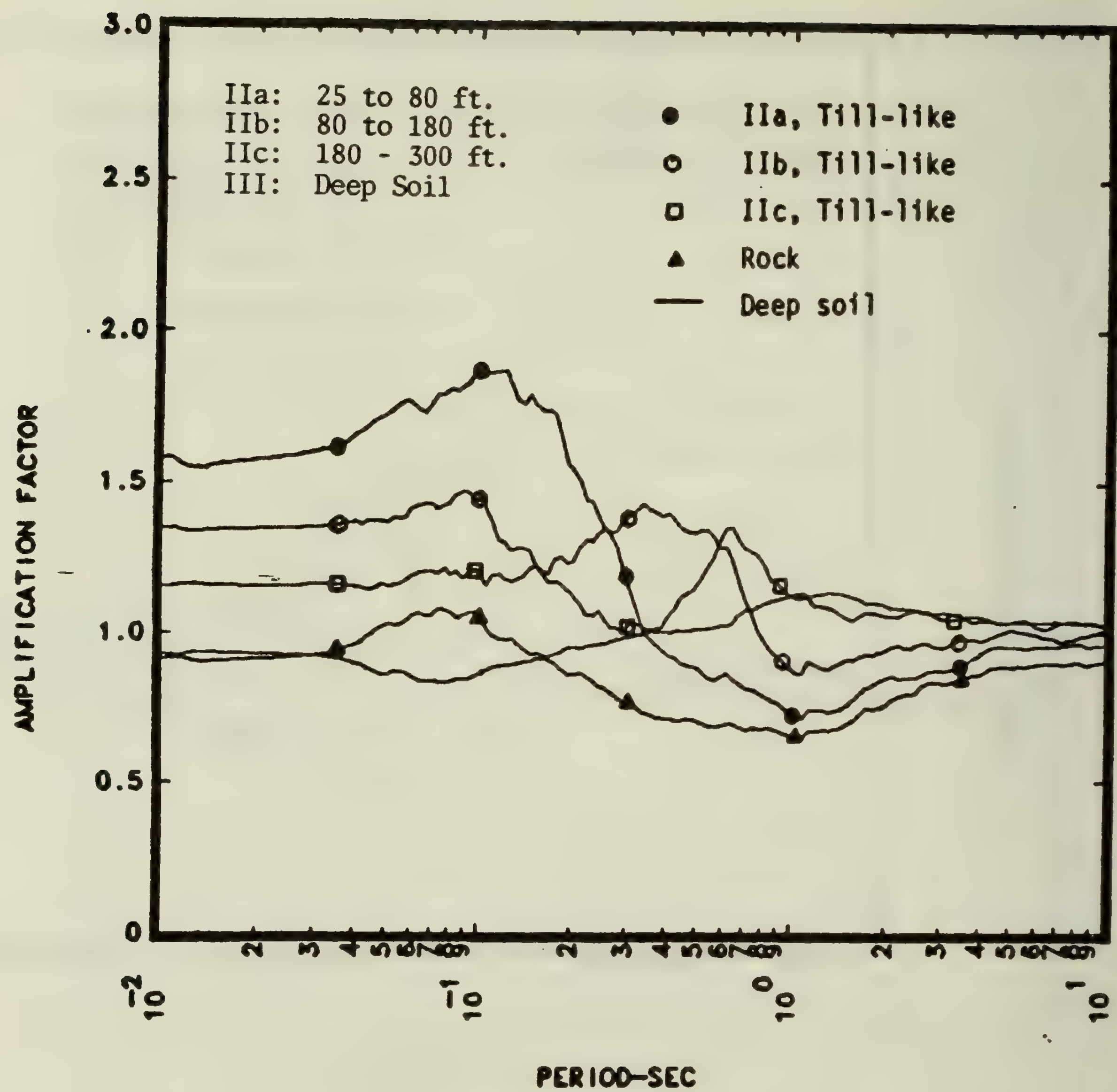


Figure 5.5b Median site correction factors for till-like categories relative to the generic soil base case.

6. QUESTIONNAIRE

6.1 Ground Motion Models

We have identified four regions in the EUS, shown in Fig. 6.1, for which it may be appropriate to change the values of some of the model coefficients, e.g., γ in the semi-empirical models. Also, a particular ground motion model may be appropriate for one region but not applicable in another. Thus, we will be asking you to select appropriate models for each of the four regions. We recognize that the actual physical situation is much more complex and the boundaries cannot be simply drawn, however, at this stage of the analysis we will limit the complexity of our model by partitioning the EUS into the four identified regions.

We have limited our analysis to the use of two "magnitude" scales, intensity (MMI) and body wave magnitude (m_b). It should be noted that (as discussed in Section 2) we are assuming m_{bLg} and m_b to be essentially equivalent. For simplicity we use the term m_b even though most of the magnitudes in the catalogs are in fact m_{bLg}.

In characterizing the seismicity within a zone, the seismicity experts expressed the earthquakes size in either magnitude or epicentral intensity. To estimate the hazard at a site it is necessary to assess the hazard based on each of the ground motion models you select. Since some ground motion models are expressed in terms of epicentral intensity and others in magnitude, a conversion of magnitude scales is required at some level. After consideration of the alternatives, we have chosen to make this conversion at the ground motion level. Thus, it is necessary to express each ground motion model in terms of both epicentral intensity and magnitude. To accomplish this conversion, we asked each member of our EUS Seismicity Panel to provide the proper conversions between scales. Since you may not feel that a ground motion model expressed in epicentral intensity to be as appropriate when converted to a model involving magnitude or vice versa, we will be asking you to select a separate set of models for intensity and magnitude.

In Question 6.1 you are requested to indicate your choices of models from those listed in Tables M6.1, M6.2, and M6.3 (note: write-in models are also acceptable) to be used in the analysis, by completing Tables Q6.1, Q6.2, and Q6.3. These tables Q6.1, 6.2 and 6.3 contain eight vertical columns to distinguish between the four regions and the two scales (m_{bLg}, MMI). In each of the eight columns please select:

- o A best estimate model
- o Up to six possible alternative models with associated levels of confidence

The best estimate model, the model to which you associate highest confidence, should represent that model which you believe best represents the average ground motion at site. Even if you believe there is no one best model but there are several comparable models, it is still necessary for you to select one model which can be used in the "best estimate" hazard analyses. Since many models have been developed based on a variety of criteria, e.g., different data sets, different parameters, you may believe that more than one model can provide useful estimates of the ground motion. Thus, you are requested to select a subset of the models from the list of models in Tables M6.1, M6.2 and M6.3. These models represent your uncertainty in estimating the expected value of ground motion at a site given the magnitude of the source and the source to site distance. You are requested to associate a "level of confidence" to each model. Your level of confidence should be based on your opinion of the data and methods used to develop the model, the ability of the model to accurately reflect the attenuation and ground motion within a region, and any other information you deem appropriate to judge the models.

When selecting the models please keep in mind their application in the hazard analysis for this project. Specifically, it should be recognized that: (1) Earthquakes are assumed to be point sources and distance is treated as epicentral distance. Thus, if you want to account for the depth of the

earthquake a depth factor should be entered into the appropriate row so that the distance metric becomes $(R^2 + \text{Depth}^2)^{1/2}$. (2) Although the seismicity panel members have revised their inputs so that the highest upper magnitude cutoff is not higher than the saturation value on the magnitude scale (approximately 7.5 m_{bLg}), the ground motion models will be assumed to be applicable over the entire range of magnitudes, 3.75-7.5 m_{bLg}. (3) Depending upon your recommendations (see Q6-5) the ground motion models will be adjusted for local site effects as follows:

- The listing of models in Tables M6.1 - M6.3 indicates what we consider to be the base case for the model (either rock or generic soil). If you disagree with our classification for any model that you have selected, please indicate what you consider to be the base case in the appropriate place in Tables Q6.1 - Q6.3.

- The appropriate local site effect correction (depending on your choice of methods of correction, see Q-6.5) will be applied for sites with soil conditions other than the base case as outlined in Section 5.

Question 6.1

For the three ground motion parameters, acceleration, velocity and spectra, please select 8 (4 regions and 2 earthquake size measures) sets of models from the models in Tables M6.1, M6.2 and M6.3 respectively by:

- Selecting a best estimate model and entering the model code, e.g. RV-5A, in the appropriate location.

- Selecting at most 6 (5 for spectra) additional models and assigning a level of confidence (weight) to each of the models (including the best estimate model) for each of the 8 columns; enter the level in the appropriate boxes in each of the columns. The sum the levels of confidence within a column must add to 1.

- Assigning an average depth for hypocentral distance models and a depth for any other model if deemed appropriate.

- Assigning a value for γ if needed for the model.

- Correcting the definition of the base case for the model if needed.

If you add a model(s) (not in the tables) please provide the model and some ID for it and enter the ID, etc. in the appropriate Table.

Note, you do not have to use different GM models or weights for the cases when the Seismicity Expert provides a recurrence model in intensity, nor do you have to have different models for the four regions. If the same, just indicate "the same" in Tables Q6.1-Q6.3.

TABLE M6.1
LIST OF PGA MODELS

1. RV MODELS -

Base case for all of the RV models is assumed to be rock.

RV-1A The Boore-Atkinson Model as described at the workshop and in Section 4.3.

RV-2A The Torro-McGuire model as described at the workshop and in Section 4.3.

RV-3A Similar to RV-1A except that Nuttli's empirical m_{Lg}-M_0 relation is used in place of the computed relation used by B-A.

RV-4A Similar to RV-2A except that Nuttli's empirical m_{Lg}-M_0 relation is used in place of the computed relation used by T-M.

RV-5A Construct your own RV-model. We need the values for (4.3.10) i.e. the relationship between M_0-f_c. We also need the relation (or how to obtain the relation) between M_0-m_{Lg}. Also, we need values for the shear wave velocity and density.

2. Direct Regression Model

DR-1A Veneziano's direct regression model as discribed at the workshop and in Section 4.1. Coefficents are given in Table 4.1.1. Two base cases-rock and soil.

3. Veneziano's Combined Model (Intensity based)

Comb-1A This is the model given in Appendix 2.

$$\ln a = 2 + 1.14\, M_{Lg} - 1.03 \ln R_h - .003\, R_h - 0.14S$$

$$R_h = (R^2 + 100)^{1/2}$$

$$S = 0 \text{ rock, } 1 \text{ soil}$$

4. <u>Semi-empirical Models</u>

SE-1A. Nuttli's (1986) model given in Appendix 3 for a f_c-M_o slope of 4
$\log (a) = 0.6 + .5\, m_b - 0.83 \log (R^2+h^2)^{1/2} - .0012R$

SE-2A. Nuttli's (1986) model given in Appendix 3 for a f_o-M_o slope of 3
$\log (a) = 1.22 + 0.375\, m_b - 0.83 \log (R^2+h^2)^{1/2} - .0012R$

Both models SE-1 and SE-2 are considered generic soil models.

The following models were discussed in our first questionnaire. Both the model number and equation number are taken from our first questionnaire- see Appendix C of Bernreuter et al. (1985). <u>We consider all of the following models to be generic soil models.</u>

<u>Subcategory II-I.</u> <u>γ Variable</u>

D11. Campbell (1981b)

$$\ln(a) = 2.64 + 0.79M - (0.023 - 0.0048M + 0.00028\, M^2)R \qquad \text{(Eq. 4-41)}$$

$$-0.862 \ln [R + 0.0286 \exp (0.778M)]$$

where R = closest distance to fault rupture

D12. Campbell (1981b)

$$\ln(a) = 4.39 + 0.922M - 0.023R + 0.0048RM - 0.00028RM^2 \qquad \text{(Eq. 4-42)}$$
$$-1.27 \ln (R + 25.7)$$

where R is epicentral distance, and for both D11 and D12

$$M = \begin{cases} 1.02\ m_b + 0.30 & (m_b < 5.59) \\ 1.64\ m_b - 3.16 & (m_b \geq 5.59 \end{cases}$$

D13. Campbell (1982) (Eq. 4-48)

$$\ln (a) = -4.29 + 0.777M - 0.797 \ln [R + 0.012 \exp (0.898M)] - \gamma R$$

where R = closest distance to fault rupture and

γ = frequency-dependent absorption coefficient (e.g. Singh and Herrman, 1983)

D14. Nuttli (1979)

$$\ln(a) = 1.481 + 1.15\ m_b - (0.0136 - 0.00172\ m_b)R \qquad \text{(Eq. 4-34)}$$
$$- 0.833 \ln R$$

D15. SSMRP

$$\ln(a) = 3.99 + 0.59\ m_b - 0.003\ (R^2 + 28.09)^{1/2} \qquad \text{(Eq. 4-37)}$$
$$- 0.833 \ln (R^2 + 28.09)^{1/2}$$

where R = closet distance to surface projection of fault rupture.

Subcategory II-2. $\gamma$and m_b Variable

D21. Nuttli (1983)

$$\ln(a) = 3.892 + 0.576\, m_b - 0.834 \ln [R^2 + \exp(-4.371 + 1.308\, m_b)]^{1/2}$$
$$-0.00281\,(r-1) \qquad m_b \le 4.4$$

$$\ln(a) = 1.313 + 1.15\, m_b - 0.833 \ln [R^2 + \exp(-7.968 + 2.100\, m_b)]^{1/2}$$
$$-\ 0.00281\,(r-1) \qquad 4.4 < m_b \le 7.4$$

Intensity Based Models

Except for the models in Subcategory I-5, a ground motion model is a combination of (a) an intensity-attenuation model and (b) a ground motion parameter-site intensity model.

Intensity Attenuation Models

A1. Bollinger (Charleston, South Carolina earthquake)

$I_s = 2.87 + I_o - 0.00052R - 1.25 \ln R$, $R \ge 10$

$I_s = I_o$, $R < 10$

A2. Bollinger (Giles County, Virginia earthquake)

$I_s = 0.35 + I_o - 0.0038R - 0.34 \ln R$

A3. Modified Gupta-Nuttli (Central U.S.)

$I_s = 3.2 + I_o - 0.0011R - 1.17 \ln R$, $R \ge 15$

$I_s = I_o$, $R \le 15$

A4. LLNL (Southern Illinois earthquake)

$I_s = 0.35 + I_o - 0.0046R - 0.31 \ln R$

A5. Weston Geophysical Corporation (Ossippee earthquake)

$I_s = 0.441 + I_o - 0.004R - 0.67 \ln R$

A6. Veneziano's fit to 4 earthquakes

$I_s = 2.41 + I_o - 1.137 \ln R - 0.0009R$

where R = hyocentral distance assuming a depth of 10 km

A7. Other - e.g. one could form models using the data from individual earthquakes given in Table 4-6 by Veneziano in Risk Eng. (1986).

Relations Between PGA and Intensity

Here we follow the breakdown used in our first questionnaire and define four subcategories. The equation numbers refer to the equation numbers given in our first questionnaire - see Appendix C of Bernreuter, et al.

Subcateogry I-1. No Weighting

G11. LLNL (1983) - Soil (Eq. 4-8)

$$\ln(a) = -1.69 + 0.86\ I_s$$

G12. LLNL (1983) -Soil (Eq. 4-9)

$$\ln(a) = -2.32 + 0.96\ I_s$$

G13. McGuire (1977) (Eqs. 4-3 and 4-7)

$\ln(a) = 0.83 + 0.85\ I_s$ (medium sites)

$\ln(a) = 0.27 + 0.6\ I_s$ (soft sites)

G14. Trifunac and Brady (1975) - Soil (Eq. 4-5)

$$\ln(a) = 0.032 + 0.69\ I_s$$

G15. Murphy and O'Brien (1977) -Soil (Eq. 4-6)

$$\ln(a) = 0.58 + 0.58\ I_s$$

G16. Trifunac (1976) (Eq. 4-4)

$$\ln(a) = -0.19 + 0.67\ I_s + 0.33S$$

$S = 0$ (alluvium)

$S = 1$ (intermediate rock sites)

$S = 2$ (basement rock sites)

Subcategory I-2. Distance Weighting

G21. Bernreuter (1981a) - Soil (Eq. 4-13)

$$\ln(a) = 1.79 + 0.57\ I_s - 0.323 \ln R$$

G22. McGuire (1977) (Eqs. 4-11 and 4-12)

$\ln(a) = 1.45 + 0.68\ I_s - 0.359 \ln R$ (medium sites)

$\ln(a) = 2.01 + 0.51\ I_s - 0.313 \ln R$ (soft sites)

Subcategory I-3. Magnitude Weighting

G31. Bernreuter (1981a) - Soil (Eq. 4-15)

$\ln(a) = 0.96 + 0.63\ I_s - 0.13\ M_L$

Subcategory I-4. Magnitude and Distance Weighting

G41. Murphy and O'Brien (1978) - Soil (Eq. 4-16)

$\ln(a) = 1.38 + 0.32\ I_s + 0.55\ M_L - 0.68 \ln R$

G42. Veneziano - based on EPRI data set. At the workshop Veneziano indicated he preferred G41 because it was based on a larger data set. However, Murphy and O'Brien did not have velocity data or spectral data to extend their model to these parameters. Hence, the Veneziano model based on the EPRI data set might be of interest.

$\ln(a) = 3.81 + 0.66\ m_b - 1.11 \ln R - 0.0024R + 0.05\ I_s + 0.18\ b_s$

$b_S = 0$ Soil; $b_S = 1$ Rock

Subcategory I-5. Semi-Empirical Intensity Models

G51. Battis (1981) - Soil (Eq. 4-29)

$\ln(a) = 3.16 + 1.24\ m_b - 1.24 \ln (R + 25)$

G52. Nuttli and Herrmann (1978) - Soil (Eq. 4-23)

$\ln(a) = 1.47 + 1.2\ m_{bLg} - 1.02 \ln R$; $R > 15$ km

G53. Weston Geophysical Corp. - Soil (Eq. 4-31)

$\ln(a) = 1.47 + 1.1\ m_b - 0.0017R - 0.88 \ln R$

TABLE M6.2

LIST OF VELOCITY MODELS

1-RV Models (all rock models)

RV-IV. The B-A model as described at the workshop and in Section 4.3.

RV-2V. The T-M model as described at the workshop and in Section 4.3.

RV-3V. Similar to RV-IV except that Nuttli's empirical M_o-m_{Lg} relation is used in place of the relation computed by B-A.

RV-4V. Similar to RV-2V except that Nuttli's empirical M_o-m_{Lg} relation is used in place of the relation computed by T-M.

RV-5V. Construct your own model. Should be consistent with your choice of parameters for RV-5a.

2-Direct Regression Model

No models developed.

3-Veneziano's Combined Model

No velocity model developed.

4-Semi-empirical Models (all soil models)

SE-IV. Nuttli's (1986) model given in Appendix 3 for a f_c - M_o slope of 4.

$$\log (v) = -3.59 + 1.0\ m_b - 0.83 \log (R^2 + h^2)^{1/2} - 0.00052R$$

SE-2V. Nuttli's (1986) model given in Appendix 3 for a f_c-M_o slope of 3.5

$$\log (v) = -2.34 + 0.75\ m_b - 0.83 \log (R^2+h^2)^{1/2} - 0.00052R$$

The following models are taken directly from our first questionnaire and have the same ID as in the first questionnaire.

Subcategory II-1.

DV11. Nutli (1979)

This model only appears in the form of a set of curves of velocity versus distance and magnitude. The reader is referred to the publication (Nuttli, 1979).

DV11. SSMRP(a)

$$\ln(v) = -7.86 + 2.3\ m_b - C_v R - .835\ \ln R$$

where $C_v = .0076 - .00099\ m_b$

DV13. SSMRP(b)

$$\ln(v) = -\ .963 + 1.15\ m_b - C_v R - .833\ \ln R$$

Subcategory II-2.

DV21. Nuttli (App. C-A)

$$= -3.11 + 1.15 m_b - 0.833\ \ln\ [R^2 + \exp(-4.371 + 1.308\ m_b)]^{1/2} - 0.00122(R-1) \qquad m_b \leq 4.4$$

$\ln(v)$

$$= -8.29 + 2.3\ m_b - 0.833\ \ln\ [R^2 + \exp(-7.968 + 2.100\ m_b)]^{1/2} - 0.00122(R-1) \qquad 4.4 < m_b < 7.4$$

5-Intensity Based Models

Attenuation of Intensity

Same as the models given in Table M6.1 Section 5.

Relation Between PGV and Intensity

Subcategory I-1. No Weighting

GV11. McGuire (1977)

$$\ln(v) = \begin{cases} -4.02 + 0.952\, I_s & \text{(medium sites)} \\ -1.51 + 0.543\, I_s & \text{(soft sites)} \end{cases}$$

GV12. Trifunac (1976)

$$\ln(v) = -2.25 + 0.67\, I_s + 0.032\, S$$

S = 0 (alluvium)

S = 1 (intermediate rock sites)

S = 2 (basement rock sites)

GV13. Trifunac and Brady (1975) - Soil

$$\ln(v) = -1.45 + 0.58\, I_s$$

Subcategory I-2. Distance Weighting

GV21. Bernreuter (1981a) - soil

$$\ln(v) = -2.94 + 0.76\, I_s + 0.06 \ln R$$

GV22. McGuire (1977)

$$\ln(v) = \begin{cases} -3.61 + 0.923\, I_s - 0.064 \ln R & \text{(medium sites)} \\ -1.11 + 0.521\, I_s - 0.072 \ln R & \text{(soft sites)} \end{cases}$$

Subcategory I-3. Magnitude Weighting

GV31. Bernreuter (1981a) - soil

$$\ln(v) = -2.62 + 0.51\, I_s + 0.17\, M_L$$

Subcategory I-4. Magnitude and Distance Weighting

(No models)

Subcategory I-5. Semi-Empirical Intensity Based Models

GV51. Nuttli - Hermann (1978) - Soil

$$\ln(v) = -6.72 + 2.3\, m_b - \ln R$$

GV52. <u>Western Geophysical Corporation</u> - Soil

$$\ln(v) = -0.924 + .95\, m_b - .0023R - .765 \ln R$$

TABLE M6.3

LIST OF RESPONSE SPECTRA MODELS

1. RV - Models (all rock models)

RV-1RS The B-A model as described at the workshop and in Section 4.3.

RV-2RS The T-M model as described at the workshop and in Section 4.3.

RV-3RS Similar to RV-1RS except that Nuttli's empirical Mo-m_{Lg} relation is used in place of the computed selection used by B-A.

RV-4RS Similar to RV-2RS except that Nuttli's empirical M_0-m_{Lg} relation is used in place of the computed relation used by T-m.

RV-5RS Construct your own model. See Model RV-5A in Table M6.1.

Semi-empirical Models

RG-RS1 Modified NRC Reg. Guide 1.60 Shape (median rather than 1-sigma) anchored to PGA - you need to specify the PGA model to be used.

ATC-RS2 ATC spectral shape anchored to PGA. You need to specify the PGA model to be used.

NH-RA3 Newmark-Hall median spectral shape anchored to PGA and PGV. You need to specify the PGA and PGV model to be used.

Intensity Based Models

As discussed in Section 4.1, a number of intensity based models can be formed by combining one of the attenuation of intensity relations A.1 - A.7 given in Table M6.1 with one of the following site intensity - GM relations listed below.

TA-RS Trifunac and Anderson (1977). Assumes a Rayleigh distribution. Model is of the form

$$\ln(Sa) = C_1 + C_2 I_s + C_3 S$$

If you select this model based on the discussion given in Section 4, please indicate if you want us to use S=0 and take generic soil as the base case or

If you want a rock base indicate how we should (or if we should) correct the empirical attenuation of intensity relation.

TL-RS Trifunac and Lee (1985). Assumes a Rayleigh distribution. Updated version of the model TA-RS. See Section 4.1.

SEP-1. Bernreuter (1981). See Section 4.1. Model of the form
$\ln(Sa) = C_1 + C_2 I_s + C_3 \ln R$
Base Case is generic soil.

SEP-2 Bernreuter (1981). See Section 4.1. Model of the form
$\ln(Sa) = C_1 + C_2 I_s + C_3 M_L$

Base case is generic soil. Unless you specify otherwise we will take $M_L = m_b$.

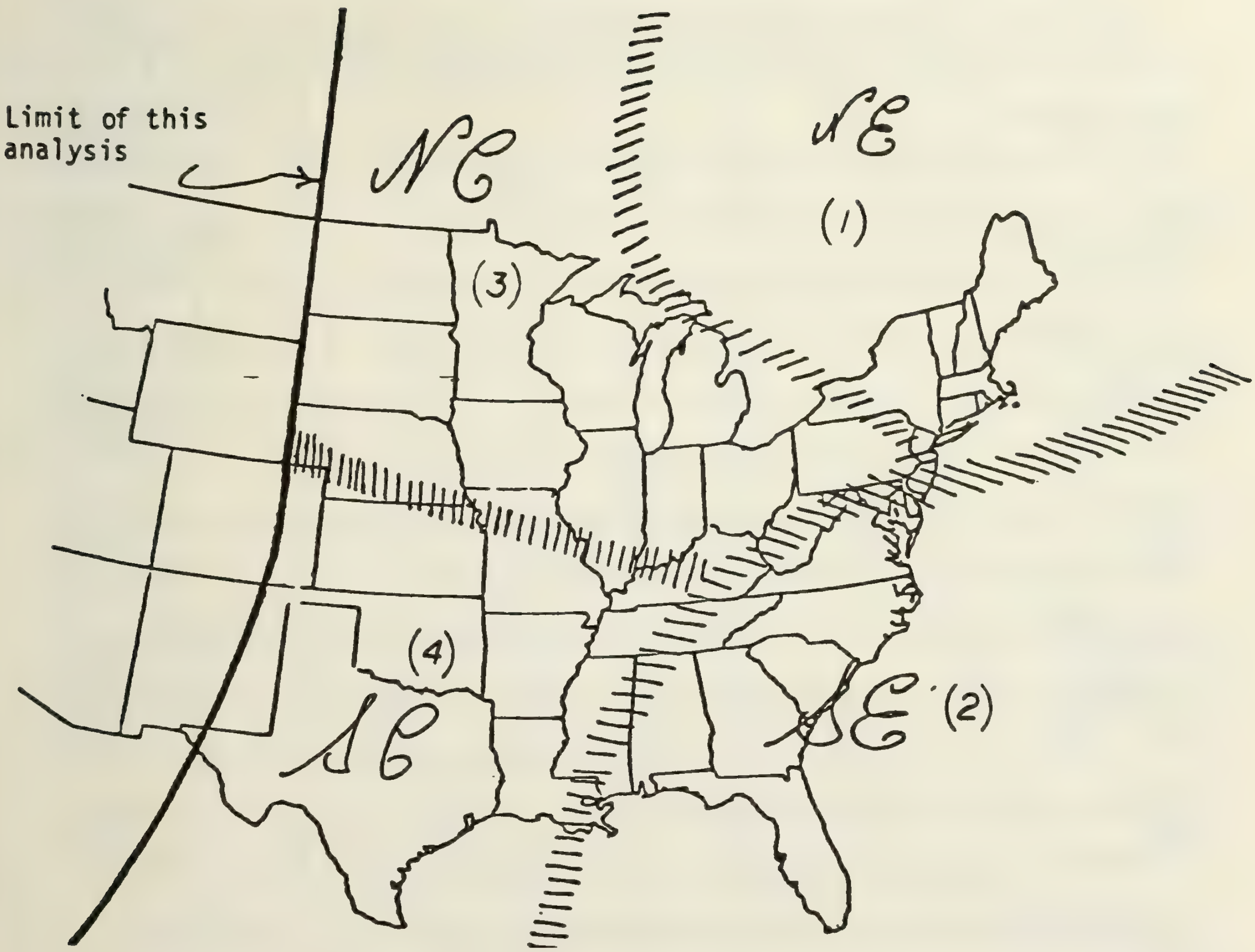


Figure 6.1 Identification of four regions of the Eastern U.S. based on a compilation of the seismic zonation experts maps developed in this study and a map of Q_0-contours from Singh & Herrmann (1983)

TABLE Q6.1

PEAK GROUND ACCELERATION MODELS

	S-Expert's Recurrence Model is in Magnitude				S-Expert's Recurrence Model is in Intensity			
	Region 1	Region 2	Region 3	Region 4	Region 1	Region 2	Region 3	Region 4
Best Estimate Model - ID								
Weight								
Average Depth if Needed								
- if Needed								
Base Case if Different								
Alternative - 1 Model - ID								
Weight								
Depth if Needed								
- if Needed								
Base Case if Different								
Alternative - 2 Model - ID								
Weight								
Depth if Needed								
- if Needed								
Base Case if Different								
Alternative - 3 Model - ID								
Weight								
Depth if Needed								
- if Needed								
Base Case if Different								

TABLE Q6.1 (Cont.)

PEAK GROUND ACCELERATION MODELS

	S-Expert's Recurrence Model is in Magnitude				S-Expert's Recurrence Model is in Intensity			
	Region 1	Region 2	Region 3	Region 4	Region 1	Region 2	Region 3	Region 4
Alternative - 4 Model - ID								
Weight								
Average Depth if Needed								
- if Needed								
Base Case if Different								
Alternative - 5 Model - ID								
Weight								
Depth if Needed								
- if Needed								
Base Case if Different								
Alternative - 6 Model - ID								
Weight								
Depth if Needed								
- if Needed								
Base Case if Different								
Sum of Weights								

NOTES: If you select intensity based models, be sure and include both the ID for the attenuation relationship and the ID for the I_S-GM, relation.

TABLE Q6.2

PEAK GROUND VELOCITY MODELS

	S-Expert's Recurrence Model is in Magnitude				S-Expert's Recurrence Model is in Intensity			
	Region 1	Region 2	Region 3	Region 4	Region 1	Region 2	Region 3	Region 4
Best Estimate Model - ID								
Weight								
Average Depth if Needed								
- if Needed								
Base Case if Different								
Alternative - 1 Model - ID								
Weight								
Depth if Needed								
- if Needed								
Base Case if Different								
Alternative - 2 Model - ID								
Weight								
Depth if Needed								
- if Needed								
Base Case if Different								
Alternative - 3 Model - ID								
Weight								
Depth if Needed								
- if Needed								
Base Case if Different								

TABLE Q6.2 (Cont.)

PEAK GROUND VELOCITY MODELS

	S-Expert's Recurrence Model is in Magnitude				S-Expert's Recurrence Model is in Intensity			
	Region 1	Region 2	Region 3	Region 4	Region 1	Region 2	Region 3	Region 4
Alternative - 4 Model - ID								
Weight								
Average Depth if Needed								
- if Needed								
Base Case if Different								
Alternative - 5 Model - ID								
Weight								
Depth if Needed								
- if Needed								
Base Case if Different								
Alternative - 6 Model - ID								
Weight								
Depth if Needed								
- if Needed								
Base Case if Different								
Sum of Weights								

NOTES: If you select intensity based models, be sure and include both the ID for the attenuation relationship and the ID for the I_s-GM relation.

TABLE Q6.3

SPECTRA MODELS

	S-Expert's Recurrence Model is in Magnitude				S-Expert's Recurrence Model is in Intensity			
	Region 1	Region 2	Region 3	Region 4	Region 1	Region 2	Region 3	Region 4
Best Estimate Model - ID								
Weight								
Average Depth if Needed								
- if Needed								
Base Case if Different								
Alternative - 1 Model - ID								
Weight								
Depth if Needed								
- if Needed								
Base Case if Different								
Alternative - 2 Model - ID								
Weight								
Depth if Needed								
- if Needed								
Base Case if Different								
Alternative - 3 Model - ID								
Weight								
Depth if Needed								
- if Needed								
Base Case if Different								

TABLE Q6.3 (Cont.)

SPECTRA MODELS

	S-Expert's Recurrence Model is in Magnitude				S-Expert's Recurrence Model is in Intensity			
	Region 1	Region 2	Region 3	Region 4	Region 1	Region 2	Region 3	Region 4
Alternative - 4 Model - ID								
Weight								
Average Depth if Needed								
- if Needed								
Base Case if Different								
Alternative - 5 Model - ID								
Weight								
Depth if Needed								
- if Needed								
Base Case if Different								
Sum of Weights								

NOTES: If you select intensity based models, be sure and include both the ID for the attenuation relationship and the ID for the I_S-GM relation.

6.2 Ground Motion Saturation

For this project, the hazard analysis has been based on modeling the ground motion parameter, given magnitude (and/or intensity) and distance, as having a lognormal distribution, i.e. as having an unbounded range. The only exception to this are the TA-RS and TL-RS spectra models where the distribution is modeled by a Rayleigh distribution. At an earlier feedback meeting some of you indicated that a more appropriate model would be one which restricted the ground motion parameter (GMP) to a finite range. To accommodate this view we propose to include a model for your consideration, a model for the GMP that has a truncated lognormal distribution. To do this it is necessary to specify an upper limit to the range of the GMP's.

Any upper limit on the range of the GMP's should be based on some interpretation of ground motion saturation. Three interpretations of saturation are proposed (Note: the discussion is given in terms of acceleration although a similar discussion holds for velocity and spectra):

Type I: There is an absolute maximum acceleration, independent of magnitude and distance, which will not be exceeded.

Type II: The maximum acceleration is a function of magnitude and distance; this will be modeled by assuming the maximum acceleration is a fixed number of standard deviations from the mean in the lognormal distribution of the GMP's.

Type III: For any magnitude and distance the maximum acceleration is the minimum of an absolute maximum and a fixed number of standard deviations from the mean; this is an envelope of Type I and II saturation.

The 3 types of limits, drawn as a function of distance R for a fixed magnitude m, are depicted in Figure 6.2:

Type I: an absolute maximum acceleration, a_1, results in the horizontal curve C_1

Type II: the maximum acceleration if a fixed number, n, of standard deviations from the mean, thus the limit curve is C_2 which "parallels" the mean curve, a(m, R)

Type III: the envelope of Type I and II, results in the curve C_3.

We would like you to consider the potential physical saturation of ground motion parameters and, if the ground motion parameters do saturate, the most appropriate way to model physical saturation. Please recognize that we will continue to assume that, given magnitude and distance, the GMP basically has a lognormal distribution. If the GMP does saturate, bounding the range implies that the distribution of the GMP will be modeled as a truncated lognormal distribution, truncated at the upper limit. The 3 types of saturations are different methods for modeling the upper limit.

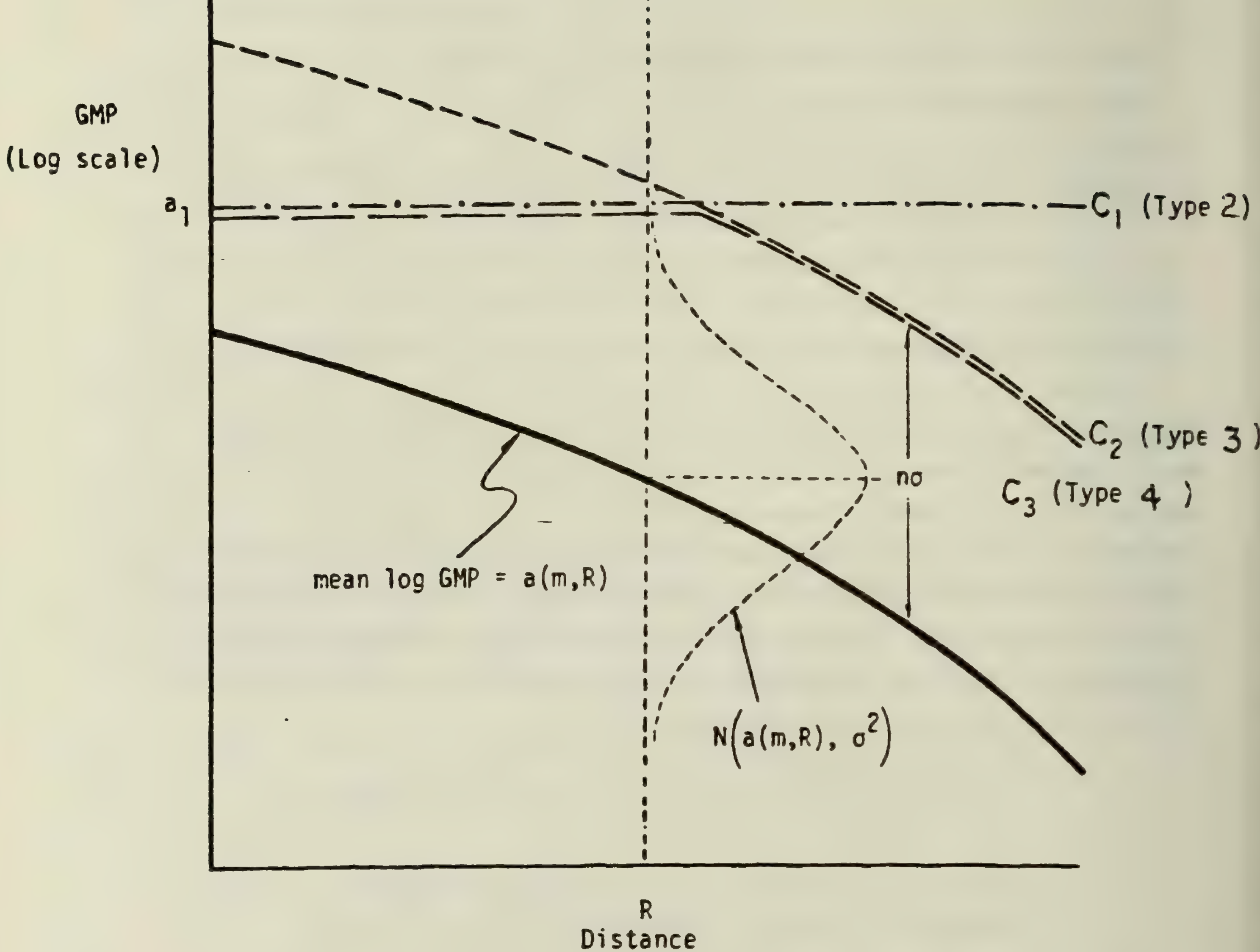


Figure 6.2 Description of the three types of models considered for the physical saturation of the ground motion. The random variation of the logarithm of the GMP is modeled by a normal distribution with mean a(m,R) and standard deviation σ.

Question 6.2

Using Table 6.4 please indicate the method you consider most appropriate for modeling the range of values for each of the ground motion parameters, acceleration, velocity and spectra. Indicate your choice by writing a check mark (✓) by the appropriate method for each ground motion parameter.

Table 6.4

Method for Describing Range of GMP	Ground Motion Parameter		
	Acceleration	Velocity	Spectra
1. GMP is not bounded; range is (0, ∞)			
2. GMP saturates; maximum is best described by a Type I limit			
3. GMP saturates; maximum is best described by a type II limit			
4. GMP saturates; maximum is best described by a Type III limit			

If you have checked method 1, no bound, in Question 6.2 for all three GMP's, please skip Question 6.3 and go to Question 6.4.

If you selected method 2,3 or 4 it is necessary to specify the parameters, i.e. a_1 or n, which characterize the upper limit. We would like you to specify a best estimate value for the appropriate parameter.

Question 6.3

In Table 6.5 please give your best estimate for the parameter(s) which characterize the method you choose for describing the upper limit of the range of each of the GMP's.

Table 6.5

	Ground Motion Parameter		
	Acceleration	Velocity	Spectra
Absolute Maximum, a_1 (Needed for method 2 & 4) (cm/s/s, cm/s, cm/s)			
Number of Standard Deviations, n (needed for method 3 & 4, n, not necessarily an integer)			

6.3 Random Variation

The hazard analysis used to construct seismic hazard curves or uniform hazard spectra at a site is based on assuming that, given a source magnitude (and/or intensity) and source to site distance, the GMP is a random variable. As indicated earlier, for this project, random variation in the GMP will generally be modeled by the lognormal (or truncated lognormal) distribution. It is recognized, per the discussion at the feedback meeting, that the unbounded lognormal distribution may not be the optimal model for describing the variation in the GMP given magnitude and distance. However, given that there is only limited information in the literature regarding alternative distributions we consider it appropriate to continue to use the lognormal distribution in the hazard analyses for this project except for the models TA-RS and TL-RS. In addition, allowing truncated lognormal distributions as alternative models introduces some flexibility which, we believe, will provide models which are more concentrated about the central value of the distribution--the characteristic observed in some plots of GM data. An important characteristic of the lognormal distribution, in addition to the description of the mean (of the log GMP) given by the ground motion model, is the measure of the random variation in the GMP. This is usually described by σ, the standard deviation of the log GMP.

Although we previously asked you to provide best estimates and uncertainty bounds, we believe it is appropriate to have you reconsider your estimates of the random variation you provided in light of what you have learned about the way LLNL uses the ground motion models in the hazard analysis, the possibility (if you indicate it is appropriate) of making local site effect corrections, or any new developments in the field of ground motion.

When assessing the value of σ there are several points which we believe you should consider:

- o Many of the ground motion models are based on fitting models to empirical data. An estimate of the "standard deviation of the error"

is a common output of the fitting process. One might consider this to be a reasonable estimate of σ. However, it should be recognized that the standard deviation of the error potentially consists of 2 components of variance -- the random variation in the GMP about its expected or average value (as estimated by the ground motion model) and the adequacy of the specific model in describing the true expected or average value of the GMP. It is important in doing the hazard analysis that only the random variation component be considered in making the probability calculations.

o What, if any, effect will correcting for local site conditions have on the level of random variation? It should be recognized that adjustments will be made, at your discretion, in the ground motion models for different types of conditions at the site. If making such adjustments will have an effect on the level of random variation, this should be recognized in assessing your estimates of σ .

o The hazard analysis assumes that the GMP random variation is independent of magnitude and distance as well as the site, although regional variation in σ is considered, and some implicit dependence on the distance may be introduced if you choose Type II or Type III saturation as an answer to Question 6.2.

o Overall, given an earthquake of a fixed magnitude and distance from the site, the GMP at the site will be affected by many factors including (1) the frequency content and other characteristics unique to each earthquake, (2) the specific travel path of the ground motion and (3) the unique soil conditions of the specific site, even if a local site correction is made -- the correction will only be made for a soil class, not for each specific site.

Question 6.4

Using Table 6.6 for each GMP and each of the 4 regions, provide your

- o best estimate of σ
- o estimate of the interval which you believe, with a high degree of confidence, represents the possible range of σ

Table 6.6

(Please be aware that σ is the standard deviation of the (natural) logarithm of the GMP)

Ground Motion Parameter		Region: Northeast	Southeast	North Central	South Central
PGA	Best Estimate:				
	Uncertainty Bounds:				
PGV	Best Estimate:				
	Uncertainty Bounds:				
Spectra	Best Estimate:				
	Uncertainty Bounds:				

6.4 Correction for Local Site Effects

At the feedback meeting and in Section 5 of this Questionnaire, three methods of adjusting (correcting) the ground motion models for different types of site conditions were discussed. One method, referred to as a "simple correction", involves making a deterministic adjustment. The second method, referred to as a "categorical correction", is based on more sophisticated analyses of the GMP's for a sample of earthquake time histories and sites.

Question 6.5

When filling in Table 6.7, you may choose one of the three methods exclusively by assigning a level of confidence of 1.0 to only one of them, or you may recommend using more than one method by assigning levels of confidence lower than 1.0, but adding to unity. In the latter case, the best estimate will be based on using the method with the highest level of confidence whereas the uncertainty analysis will be based on randomizing between the selected methods. And to avoid any ambiguity by possibly having several equal highest levels of confidence, please fill the bottom box to indicate your best estimate. For the simple correction approach please indicate which correction curve you want to use based on the choice given in Fig. 6.3. If you want some other correction factors please provide a plot similar to Fig 6.3.

Table 6.7

Methods of Adjustment		Ground Motion Parameter		
Index	Type	Acceleration	Velocity	Spectra
1	No correction			
2	Simple correction			
3	Categorical correction			
	Your Best estimate method (Please indicate 1, 2 or 3			
	ID for set of simple correction factors to use from Fig. 6.3			

6.5 Self-Rating

In our hazard analysis it will be necessary to combine the hazard at a site based on the different ground motion models chosen by a panel member as well as combining over the opinions provided by all panel members. Combining the hazard estimated using the different models suggested by an individual member will be based on the confidence levels you provide. To combine over all the panel members we propose to use a weighted average procedure. Of course, this requires an appropriate set of weights.

Although there are several weighting schemes (e.g., equal weights, LLNL derived weights), the set of weights we propose to use is based on your appraisal, i.e., self-rating, or your expertise about the utility of ground motion models, method of site correction, etc.

We recognize some of the weaknesses and difficulties in eliciting and using self-rating, however, most alternative weighting schemes are also subjective and involve some of the same problems as self-rating. Overall, we believe self-rating to be a viable means of developing weights for combining the results derived from your opinions about the ground motion models. Thus, we would like you to indicate your level of expertise with regard to assessing the utility of the ground motion models.

In appraising your level of expertise, we ask that you use a 0-10 scale where low values indicate a low level of expertise and high values a high level of expertise. An integer value is not necessary.

Question 6

Please indicate your level of expertise, relative to the scientific community at large, with regard to the several issues for which your opinions have been elicited. Please use a scale of 0 to 10, with 10 indicating a "high" level of expertise.

Level of expertise: ________________

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APPENDIX 1

Letter from D.L. Bernreuter to D. Veneziano

Lawrence Livermore National Laboratory

NUCLEAR SYSTEMS SAFETY PROGRAM

December 3, 1986
EG-86-197

Dr. Daniele Veneziano
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MIT
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Dear Daniele:

I want to thank you for participating in our Ground Motion Workshop. Your contribution was most helpful. As I understand your presentation, you prefer your post- EPRI model (E+) over the EPRI model (E). However, it is not clear from your handouts which (E+) model, 1. Diag. COV or 2. Full COV, you think is best. Also, do you recommend using the S_V (10) and S_V (1) models you developed for EPRI along with your preferred (E+) model to compute the spectra? If not, what do you recommend, keeping in mind that spectra are very important to our effort?

I also have a question. Namely, it seems to me that in developing your EUS indirect models, both (E) and (E+), you have violated the point you made that when using the indirect path it is necessary that the same independent variables be included in both regression models. Specifically, in the regression for I_S you only have R and I_O or M as independent variables and not the parameters V and S. However in the regression model for say acceleration you have I_S, R, M, V and S. The component parameter, V, is probably not important thus one could argue that its coefficent is zero and hence one can constrain $b_V = 0$ in the regression model for I_S as you did. Such is definitely not the case for site soil effects. The soil type is important. Thus it is not possible to argue that it is reasonable to set the coefficent of S, b_S, to zero as you did in the regression model for I_S. The net result of your substitution seems to lead to an erroneous result. For example, the relation

$$Y = f_1 (I_S, M,R,S,V) \tag{1}$$

found by Murphy and O'Brien seems OK, in that for the same M,R and I_S, rock sites have a higher acceleration than soil sites. However when

$$I_S = f_2 (M, R) \tag{2}$$

is substituted into (1) to get the relation

$$Y = f_3(M,R,S,V) \tag{3}$$

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e.g. the model you label indirect (E+)

$$\ln a = 1.4 + 1.18M - .003R - 1.04 \ln R - 0.4S \qquad (4)$$

a problem appears to arise. The problem with this model (4) is that at the same M and R the acceleration at soil sites is 1.5 times smaller than at rock sites. This is in disagreement with most results which have the acceleration either the same or slightly smaller at rock sites than at soil sites. This contradiction arises because most of the sites with intensity data used to establish the coefficents of Eq. (2) are soil sites. Thus Eq. (2) essentially has "soil" as the base case. It is generally agreed, that at the same M and R, I_S for rock sites is 1/2 to 1 units smaller than for soil sites. Thus if these corrections were made then the site correction factor in Eq. (2) would "cancel" the correction in Eq. (1) when the two equations are combined such that the resulting acceleration at soil and rock sites would almost be the same. My question is, do you agree with the above analysis or is there some other reason for the apparently contradictory result obtained by Eq. (4) as compared to other models?

I hope I have made my questions clear. If not, please give me or Jean a call. I am looking forward to hearing from you in the near future.

Sincerely,

Don

Don L. Bernreuter, Leader
Engineering Geosciences Group

DLB:sc
cc: J. Savy, LLNL

APPENDIX 2

Letter from D. Veneziano to D.L. Bernreuter

DEPARTMENT OF CIVIL ENGINEERING
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS 02139
Room 1-380

December 24, 1986

Dr. Don L. Bernreuter, Leader
Engineering Geosciences Group
Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, California 94550

Dear Don:

Thank you for your letter of December 3 on the ground motion model we developed for ENA. Your points are well taken; in response to them, we have made a few additional runs and obtained slighly different results for PGA.

The coefficient of V in the attenuation of I_s is theoretically zero, but the coefficient of S is not. The value of the latter coefficient ,say b_s, was set to zero on the basis of a detailed study of a large data set from Northeastern Italy, where we have found that the coefficients of site-geology indicators (rock, alluvium of different thickness) are not significantly different from zero. This may however be a peculiarity of that region and should not be taken as a general conclusion.

In rerunning our program, we have considered b_s to be uncertain, with mean zero and standard deviation either 1.0 or 2.0. The method then estimates b_s together with the other coefficients. The results of the two runs and of the run of our previous analysis with σ_{bs}= 0 are given in Table 1. These runs are for the case for "Full Covariance" matrix of the Murphy-O'Brien coefficients, which in the case we prefer.

Each output includes an echo-print of the input relationships (mean values of the parameters prior to conbining direct and indirect information) and the corresponding output relationships (mean values after combination). The final attenuation model ℓn PGA (M,R,V,S) is indicated by an arrow. It is interesting that, when σ_{b_s} is set to 1.0 or to 2.0, the coefficient b_s is estimated by the method to be positive (respectively 1.00 and 1.91), with consequent reduction of the coefficient of S in the attenuation of PGA. This is as you suggested it should be. We concur and propose to use the results for σ_{b_s}= 1.0 as best estimates. Therefore our model becomes

$$\ell n \text{ PGA } (\text{cm/sec}^2) = 2.00 + 1.14\, m_{Lg} - 1.03\, \ell n\, R_h - 0.003\, R_h - 1.12V - 0.14S \quad (\sigma = 0.65)$$

where R_h is hypocentral distance in kilometers, and V and S are indicator variables for vertical component and soil, respectively. Plots that compare the direct, indirect, and combined PGA models for roch and soil sites are

To Don L. Bernreuter
December 24, 1986
Page Two

shown in Figure 1. The coefficients of m_{Lg} and R_h are similar in all three models. With respect to the coefficent of $\ell n\ R_h$, the combined model is closer to the indirect model, whereas for the coefficient of V and the overall "location", the combined model is most similar to the direct model. The coefficient of S is intermediate between the direct and indirect estimates. The covariance matrix of the regression coefficients and residual variance is given in Table 2. This matrix may be used to express uncertainty on the attenuation function, e.g. by using Monte Carlo simulation from a multivariate normal distributions.

For S_{v1} and S_{v10}, reliable indirect estimates cannot be obtained. Therefore, we suggest that the direct regressions and associated covariance matrices be used. The mean relationships are:

$$\ell n\ S_{v_1}(\text{cm/sec}) = -8.51 + 2.22\ m_{Lg} - 0.843\ \ell n\ R_h - 0.003\ R_h - 1.01\ V + 0.91S \quad (\sigma=0.98)$$

$$\ell n\ S_{v_{10}}(\text{cm/sec}) = -2.85 + 1.27\ m_{Lg} - 0.886\ \ell n\ R_h - 0.003\ R_h - 1.12V + 0.20S \quad (\sigma=0.46)$$

and the covariance matrices of the regression coefficients and residual variance are given in Table 3.

We appreciate this opportunity to refine our analysis and thank you again for your constructive criticism.

Sincerely,

Daniele Veneziano

Daniele Veneziano
Professor of Civil Engineering

DV:ccc
Encl.

$\sigma_{b_s} = 0$

```
( IS/ IO   R  LnR   S  COM   M  )  WEIGHT=  1.000
 INPUT:   2.4070  1.0000 -0.0009 -1.1370  0.0000  0.0000  0.0000  1.2500
OUTPUT:   2.4090  1.0000 -0.0009 -1.1340  0.0000  0.0000  0.0001  1.1657
( IO/ M  LnR  R   COM  S   )  WEIGHT=  1.000
 INPUT: -3.6150  1.9710  0.0000  0.0000  0.0000  0.0000  0.6000
OUTPUT: -3.6086  1.9710  0.0000  0.0000  0.0000  0.0000  0.6001
(PGA/ M    R  LnR COM  S   )  WEIGHT=  1.000
 INPUT:  1.9786  1.2371 -0.0030 -1.1766 -1.1691  0.1308  0.3200
OUTPUT:  2.0771  1.1227 -0.0031 -1.0210 -1.1232 -0.3120  0.4189
(PGA/ M   R  LnR COM  S    IS )  WEIGHT=  1.000
 INPUT:  1.7840  0.5500  0.0000 -0.6800  0.0000 -0.4000  0.3200  0.4800
OUTPUT:  2.4266  0.5485 -0.0028 -0.6906 -1.1232 -0.3120  0.2913  0.2690
```

$\sigma_{b_s} = 1.0$

```
( IS/ IO   R  LnR   S  COM   M  )  WEIGHT=  1.000
 INPUT:   2.4070  1.0000 -0.0009 -1.1370  0.0000  0.0000  0.0000  1.2500
OUTPUT:   2.3675  1.0000 -0.0009 -1.1261  1.0008  0.0000  0.0005  1.1600
( IO/ M  LnR  R   COM  S   )  WEIGHT=  1.000
 INPUT: -3.6150  1.9710  0.0000  0.0000  0.0000  0.0000  0.6000
OUTPUT: -3.6103  1.9710  0.0000  0.0000  0.0000  0.0000  0.6000
(PGA/ M    R  LnR COM  S   )  WEIGHT=  1.000
 INPUT:  1.9786  1.2371 -0.0030 -1.1766 -1.1691  0.1308  0.3200
OUTPUT:  1.9966  1.1377 -0.0032 -1.0269 -1.1272 -0.1453  0.4241
(PGA/ M   R  LnR COM  S    IS )  WEIGHT=  1.000
 INPUT:  1.7840  0.5500  0.0000 -0.6800  0.0000 -0.4000  0.3200  0.4800
OUTPUT:  2.3672  0.5498 -0.0029 -0.6911 -1.1272 -0.4438  0.2982  0.2676
```

$\sigma_{b_s} = 2.0$

```
( IS/ IO   R  LnR   S  COM   M  )  WEIGHT=  1.000
 INPUT:   2.4070  1.0000 -0.0009 -1.1370  0.0000  0.0000  0.0000  1.2500
OUTPUT:   2.3330  1.0000 -0.0010 -1.1197  1.9058  0.0000  0.0001  1.1591
( IO/ M  LnR  R   COM  S   )  WEIGHT=  1.000
 INPUT: -3.6150  1.9710  0.0000  0.0000  0.0000  0.0000  0.6000
OUTPUT: -3.6120  1.9710  0.0000  0.0000  0.0000  0.0000  0.6000
(PGA/ M    R  LnR COM  S   )  WEIGHT=  1.000
 INPUT:  1.9786  1.2371 -0.0030 -1.1766 -1.1691  0.1308  0.3200
OUTPUT:  1.9538  1.1416 -0.0032 -1.0268 -1.1191  0.0042  0.4244
(PGA/ M   R  LnR COM  S    IS )  WEIGHT=  1.000
 INPUT:  1.7840  0.5500  0.0000 -0.6800  0.0000 -0.4000  0.3200  0.4800
OUTPUT:  2.3366  0.5517 -0.0030 -0.6917 -1.1191 -0.5661  0.2993  0.2668
```

Table 1 - Three analyses for PGA. Preferred case is that with $\sigma_{b_s} = 1.0$

	mean	standard deviation	correlation matrix						
b_0	0.200E+01	0.368E+00	1.00	-0.76	-0.08	-0.04	-0.04	-0.33	-0.19
b_M	0.114E+01	0.694E-01	-0.76	1.00	0.04	-0.40	0.02	0.10	0.31
b_R	-0.319E-02	0.900E-03	-0.08	0.04	1.00	-0.13	-0.09	-0.02	0.03
$b_{a,R}$	-0.103E+01	0.515E-01	-0.04	-0.40	-0.13	1.00	-0.05	-0.13	-0.24
b_V	-0.112E+01	0.269E+00	-0.04	0.02	-0.09	-0.05	1.00	0.07	0.01
b_S	-0.144E+00	0.267E+00	-0.33	0.10	-0.02	-0.13	0.07	1.00	0.05
σ_ε^2	0.424E+00	0.652E-01	-0.19	0.31	0.03	-0.24	0.01	0.05	1.00

Table 2. Final model for PGA

MODEL 4: $\ln S_V(10)(m_{Lg},R,V,S)$

	b_o	b_m	b_R	$b_{\ell nR}$	b_V	b_S	σ_ε^2
STD:	1.024	0.192	0.001	0.174	0.288	0.401	0.096
CORRELATION MATRIX							
	1.000	-0.842	0.107	-0.362	0.028	-0.103	0.000
	-0.842	1.000	0.004	-0.137	0.018	0.134	0.000
	0.107	0.004	1.000	-0.304	-0.025	0.037	0.000
	-0.362	-0.137	-0.304	1.000	-0.131	-0.309	0.000
	0.028	0.018	-0.025	-0.131	1.000	0.094	0.000
	-0.103	0.134	0.037	-0.309	0.094	1.000	0.000
	0.000	0.000	0.000	0.000	0.000	0.000	1.000

MODEL 5: $\ln S_V(1)(m_{Lg},R,V,S)$

	b_o	b_m	b_R	$b_{\ell nR}$	b_V	b_S	σ_ε^2
STD:	1.695	0.339	0.001	0.221	0.295	0.331	0.302
CORRELATION MATRIX							
	1.000	-0.897	0.085	-0.281	0.015	-0.047	0.000
	-0.897	1.000	0.011	-0.121	0.000	0.037	0.000
	0.085	0.011	1.000	-0.303	-0.006	0.022	0.000
	-0.281	-0.121	-0.303	1.000	-0.062	-0.122	0.000
	0.015	0.000	-0.006	-0.062	1.000	0.023	0.000
	-0.047	0.037	0.022	-0.122	0.023	1.000	0.000
	0.000	0.000	0.000	0.000	0.000	0.000	1.000

Table 3 - Uncertainty on coefficients for Sv_1 and Sv_{10}

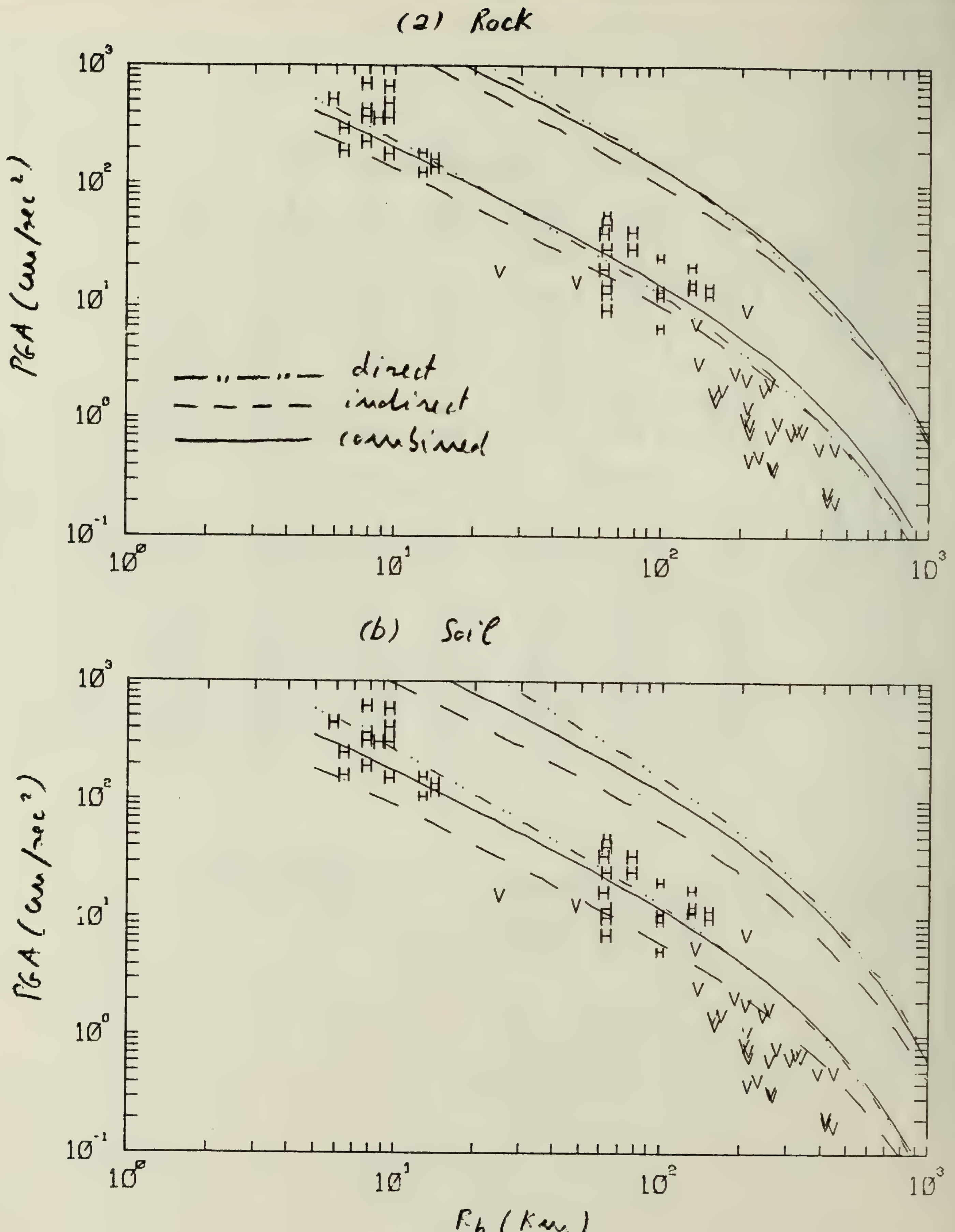


Figure 1 - Comparison of direct, indirect and combined models

APPENDIX 3

Letter from O. Nuttli to J. Savy

SAINT LOUIS UNIVERSITY

DEPARTMENT OF EARTH AND ATMOSPHERIC SCIENCES

3507 LACLEDE AVENUE
SAINT LOUIS, MISSOURI 63103

MAILING ADDRESS:
P. O. BOX 8099 – LACLEDE STATION
SAINT LOUIS, MISSOURI 63156

September 19, 1986

Dr. Jean Savy, 196
Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA 94550

Dear Jean,

Encleased is the material on spectral scaling and strong ground motion relations that I promised to send to you. It represents a revision of my earlier work.

Two things caused me to make the changes. One, the measurements of spectral corner frequencies from strong-motion data by the USGS people at Menlo Park indicated that, for a given moment, my old relations predicted too low a corner frequency for the smaller earthquakes. Two, attenuation studies by Hasegawa, by Gupta and his Teledyne Geotech colleagues, and by Chun of the University of Toronto caused me to make a slight change in average Q for eastern North America, namely $Q(f) = 1000\ f^{0.3}$. Previously I used values of 1500 and 0.4.

Enclosed is a copy of a figure from Haar et al (BSSA, Feb. 1986) showing seismic moment versus corner frequency. On it I plotted three lines, of slope 3.0, 3.5 and 4.0. All curves are anchored at the 1 Hz, 10^{23} dyne-cm value, which I believe is fairly reliable. It is difficult to choose between the curves, but I lean towards those of slope 3.5 to 4.0.

Also enclosed is a figure of m_b versus M_o, using data from a recent report by Johnston and Metzger for EPRI for global continental mid-plate earthquakes. In this figure I definitely favor the curves corresponding to an f_c-M_o slope of 4.0 or 3.5. Some of the points that plot to the left of the figure (the 3.0 curve) are from earthquakes in transition regions (neither mid-plate or plate-margin). A similar figure, from my 1983 mid-plate scaling paper, shows my new fits to the data. There is a problem, likely in the M_o values, for the small earthquakes of m_b less than 4.

The last two figures are my new spectra for mid-plate earthquakes, one for an f_c-M_o slope of 3.5 and the other for a slope of 4.0.

Probably of most interest to you and Don are the strong-ground-motion equations. Assuming that $Q(f) = 1000\ f^{0.3}$, and that peak acceleration (particularly at distances of 100 km and greater) has an average frequency of 5 Hz, peak velocity an average frequency of 1.5 Hz, and peak displacement an average frequency of 0.5 Hz, the relations are:

$$\log_{10} a_h \; (\mathrm{cm/sec^2}) = 0.60 + 0.50\, m_b - 0.83 \log (R^2 + h^2)^{\frac{1}{2}} - 0.00120\, R \quad \text{for a slope of } 4.0$$
$$\log_{10} a_h \; (\mathrm{cm/sec^2}) = 1.22 + 0.375\, m_b - 0.83 \log (R^2 + h^2)^{\frac{1}{2}} - 0.00120\, R \quad \text{for a slope of } 3.5$$

$$\log_{10} v_h \; (\mathrm{cm/sec}) = -3.59 + 1.00\, m_b - 0.83 \log (R^2 + h^2)^{\frac{1}{2}} - 0.00052\, R \quad \text{for a slope of } 4.0$$
$$\log_{10} v_h \; (\mathrm{cm/sec}) = -2.34 + 0.75\, m_b - 0.83 \log (R^2 + h^2)^{\frac{1}{2}} - 0.00052\, R \quad \text{for a slope of } 3.5$$

$$\log_{10} d_h \; (\mathrm{cm}) = -6.81 + 1.50\, m_b - 0.83 \log (R^2 + h^2)^{\frac{1}{2}} - 0.00024\, R \quad \text{for a slope of } 4.0$$
$$\log_{10} d_h \; (\mathrm{cm}) = -4.43 + 1.025\, m_b - 0.83 \operatorname{Log} (R^2 + h^2)^{\frac{1}{2}} - 0.00024\, R \quad \text{for a slope of } 3.5$$

where h is focal depth, in km, and R is epicentral distance, in km. The curves are anchored by the empirical data for an $m_b = 5.0$ earthquake, as given in the 1984 ASCE paper by Bob Herrmann and myself.

The equations for a slope of 4.0 are the more conservative, and are close to those in the 1984 ASCE paper. Chael, of Sandia Laboratories, at the 1986 Charleston SSA meeting, suggested a slope between 3 and 4. He submitted the manuscript to the BSSA, but I don't know its status. My intuitive feeling is that eventually a slope of 3.7 to 3.8 will prove the best fitting for all the mid-plate earthquake data.

I look forward to seeing you in St. Louis.

Sincerely,

Otto

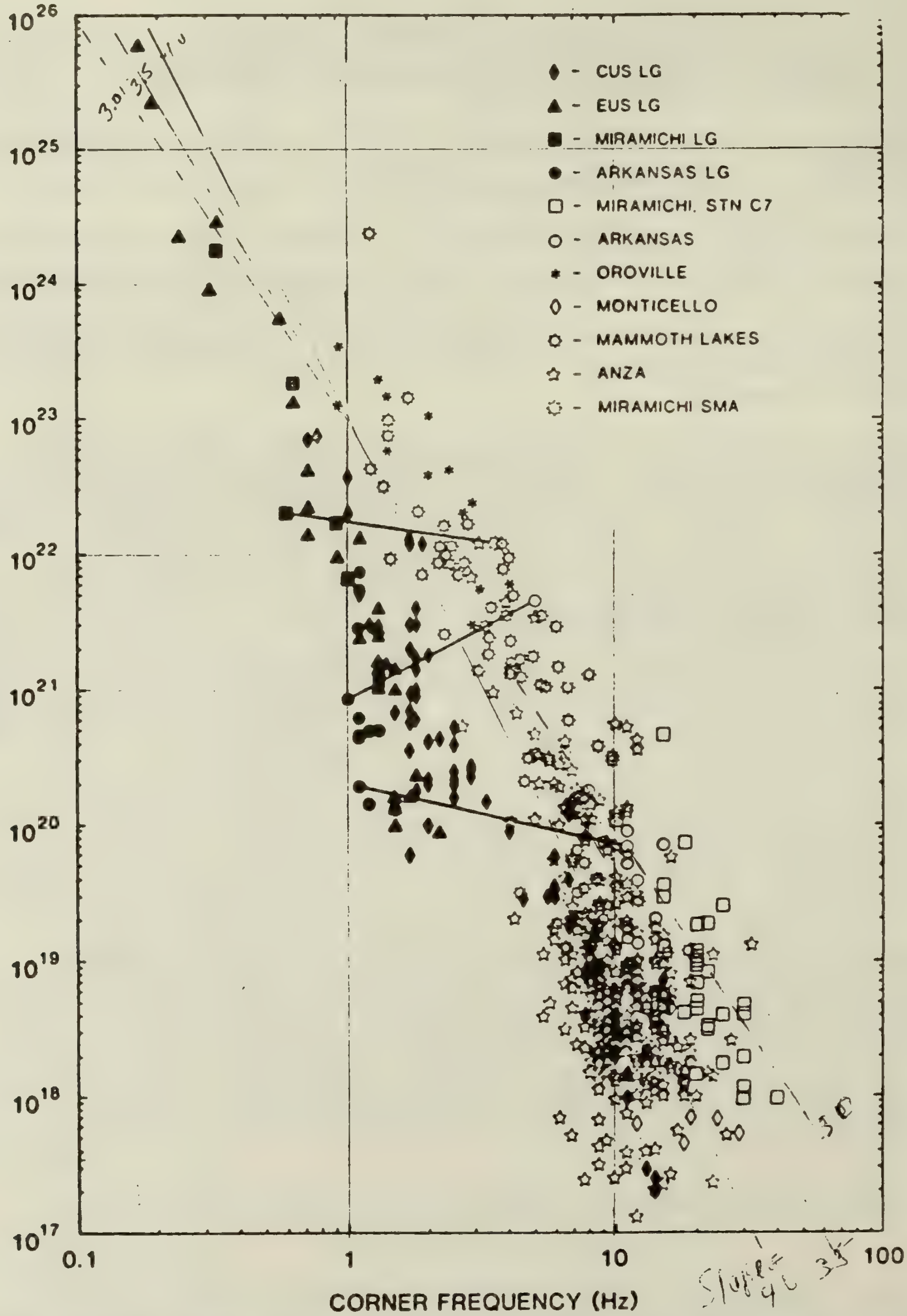
Otto W. Nuttli

Enclosures

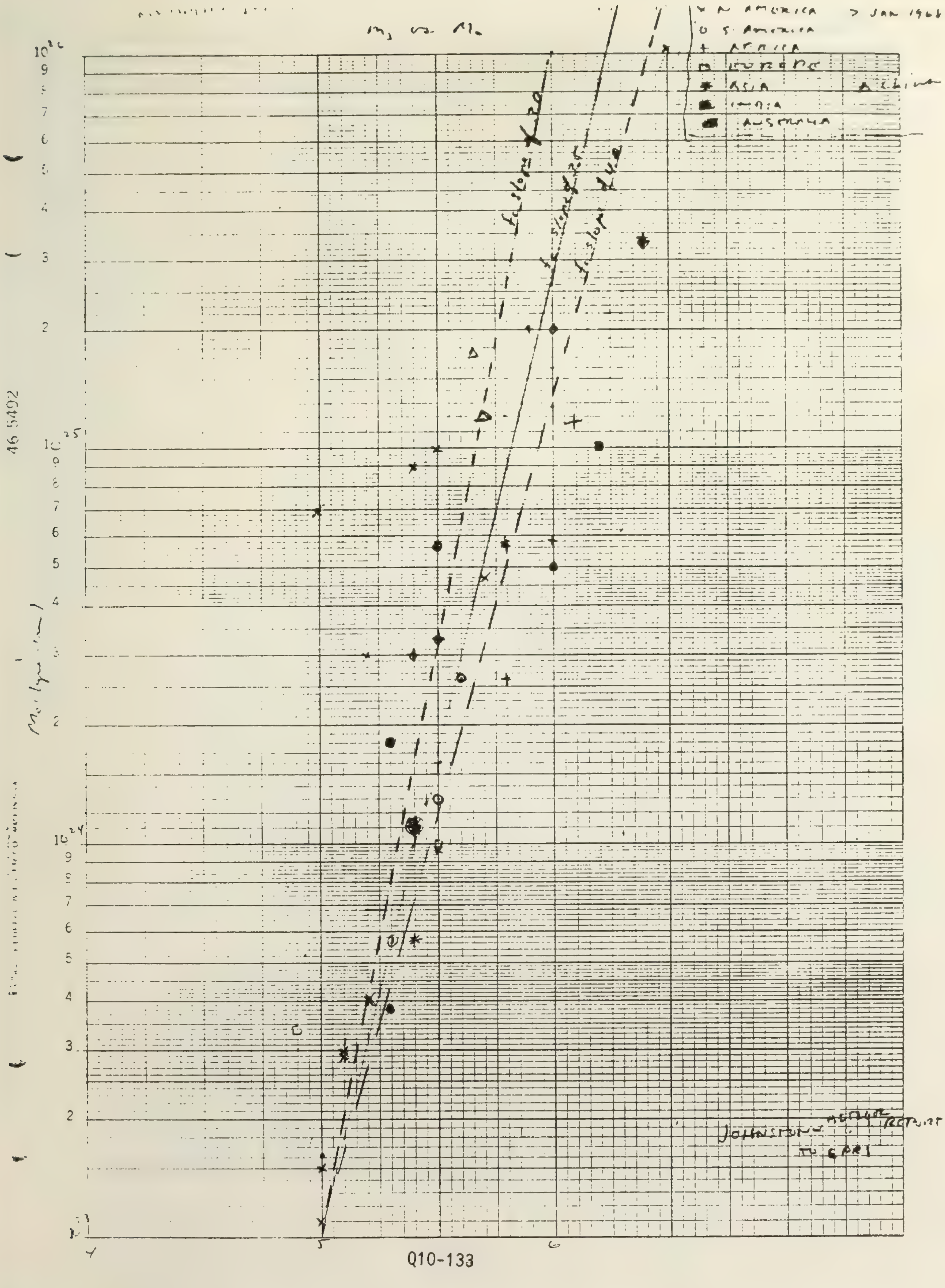
P.S. I received the EPRI seismicity catalogs from you, and have marked what I believe are some discrepancies for CUS earthquakes of $m_b \geq 4.5$.

(1984) finds that the Arkansas and Mirami... ea... spectra from

Haar et al (1986 BSSA - Feb)



smic moment versus source radius for Arkansas local recordings (Haar *et al.*, 1984), Street, 1984), Miramichi, New Burnswick local recordings (all but the largest event; 'ranswick, 1985, largest event; Boatwright, personal communication), Miramichi, New Street, 1984) Northeastern United States *Lg* (Street and Turcotte, 1977), Central United et *et al.*, 1975), Monticello, South Carolina, local recordings (Fletcher, 1982; Fletcher et Aammoth Lakes, California local recordings (Archuleta *et al.*, 1982). Oroville, California, ; (Fletcher, 1980; Fletcher *et al.*, 1983 a, b), and Anza, California, local recordings (Fletcher ation).



M_s vs. M_o
N. AMERICA
S. AMERICA
AFRICA
EUROPE
ASIA
INDIA
AUSTRALIA
China

Q10-133

For the proposed relation, a T_{02} value of [illegible] corres[illegible] to an m_b of 4.5, nearly identical to the $m_b = 4.4$ value proposed by Street [illegible] 1977) for northeastern United States earthquakes. Hasegawa (1983), in a study of Lg spectra of eastern Canadian earthquakes, observed a change in the relation of M_0 to T_{02},

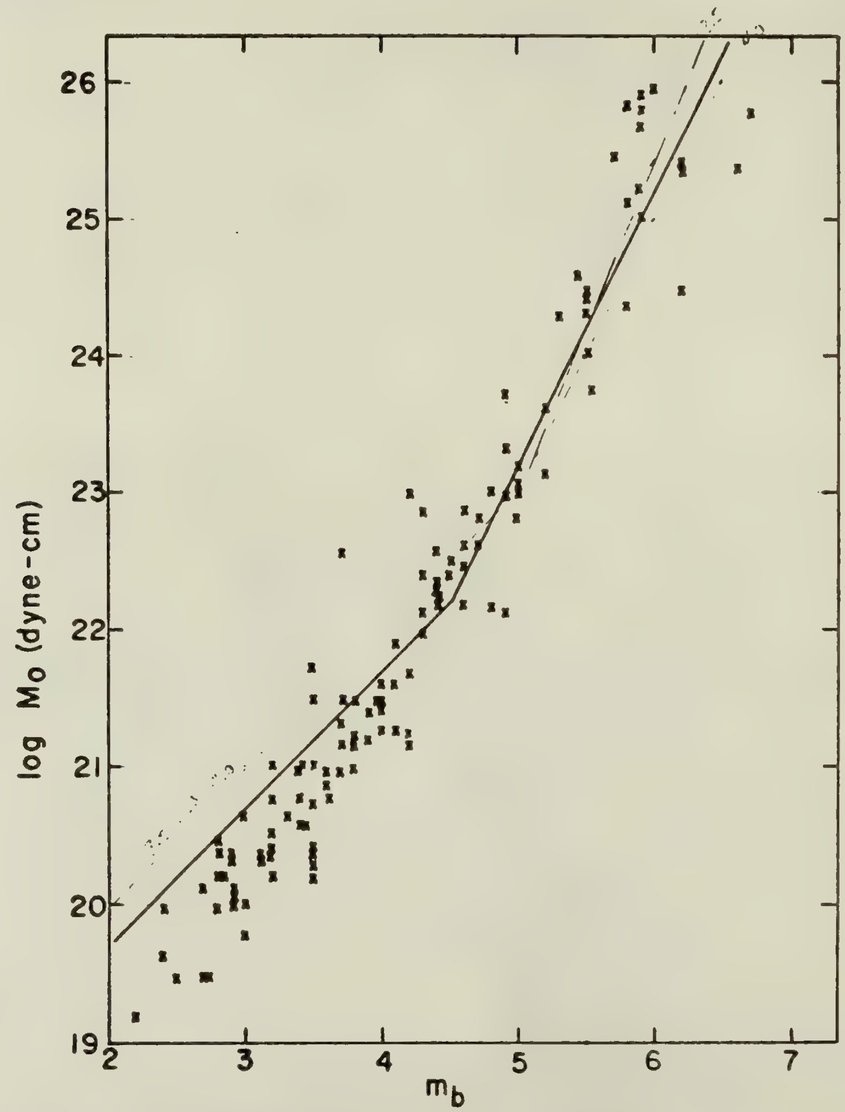
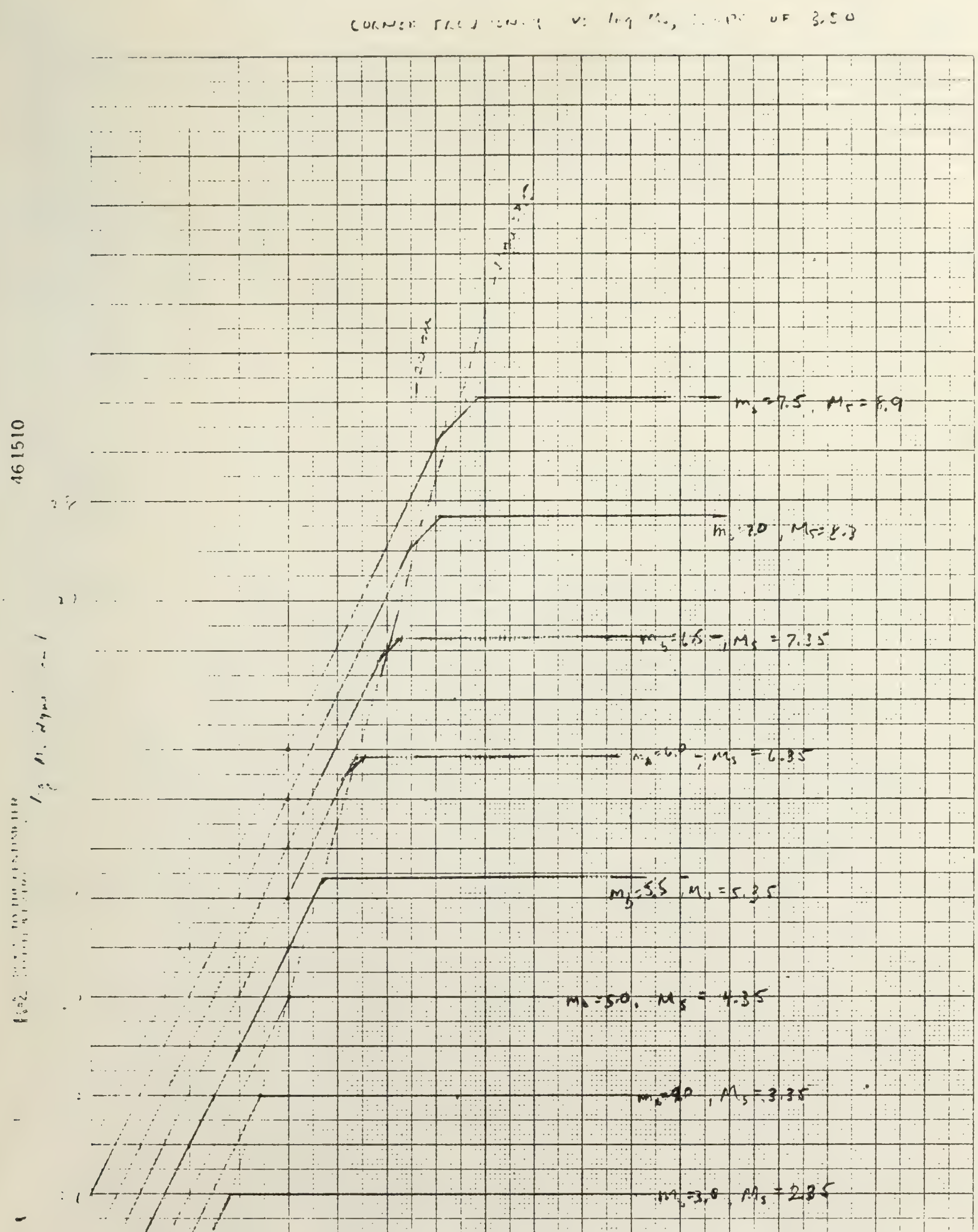
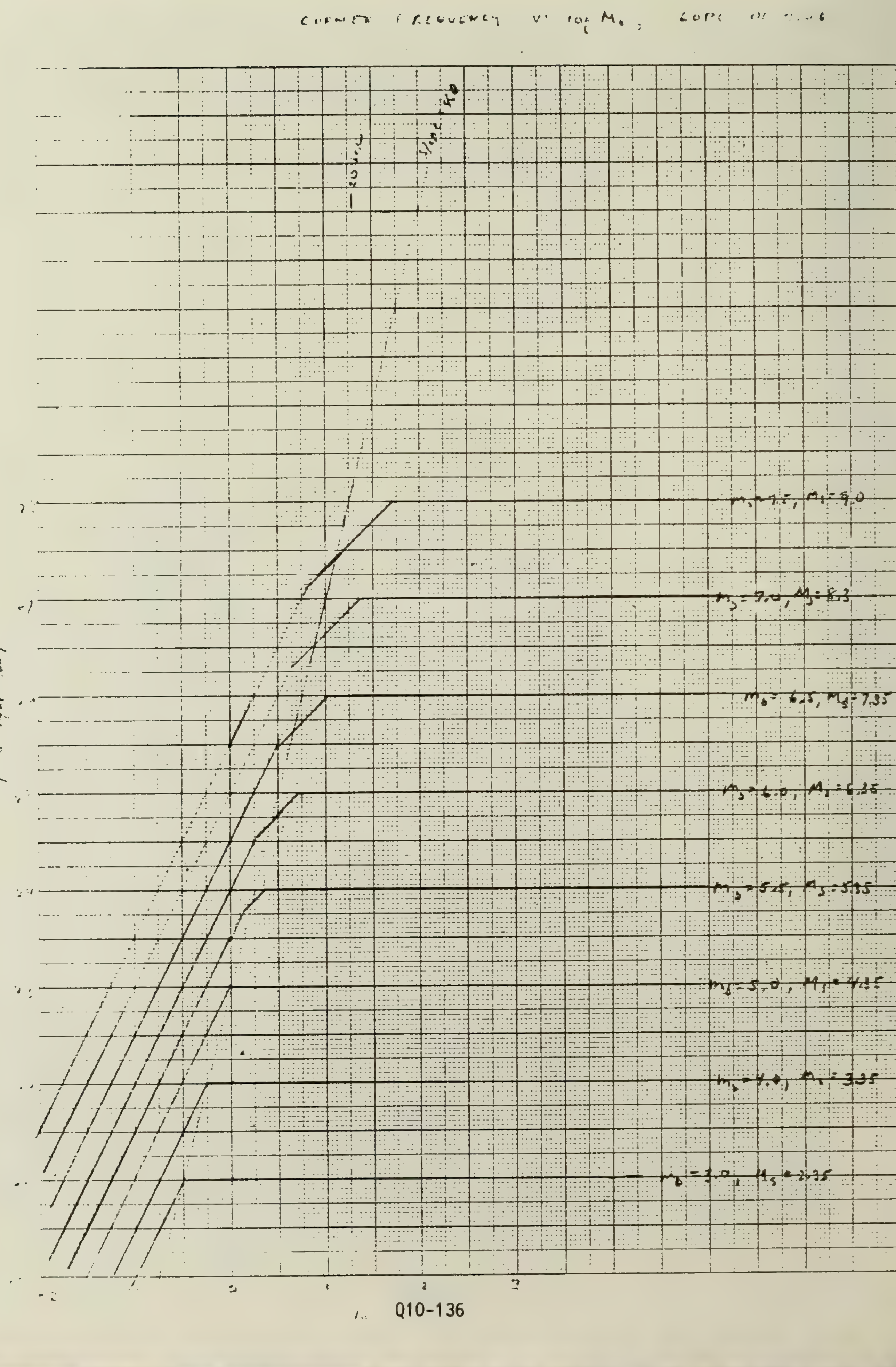


FIG. 2. m_b versus $\log_{10} M_0$ for mid-plate earthquakes. The straight-line segments are obtained from the spectral scaling relation given in Figure 5.

corresponding to m_b values of about 4.5. The data of Figure 4 conforms to the curve derived from the spectral scaling relations for $M_0 > 10^{23}$ dyne-cm. For smaller earthquakes, the corner periods, T_{02}, determined by Street *et al.* (1975) and Street and Turcotte (1977) from the spectra of Lg waves, show that the former agree with this study but that the latter are in general greater than predicted by the spectral scaling relation. An exception is the point for $M_0 = 1.5 \times 10^{19}$ dyne-cm, corresponding to the very shallow Rhode Island earthquake of 11 March 1976. The data taken from Fletcher (1982) are for very shallow-induced earthquakes at the Monticello


$m_b = 7.5$, $M_s = 8.9$
$m_b = 7.0$, $M_s = 8.3$
$m_b = 6.5$, $M_s = 7.35$
$m_b = 6.0$, $M_s = 6.35$
$m_b = 5.5$, $M_s = 5.35$
$m_b = 5.0$, $M_s = 4.35$
$m_b = 4.0$, $M_s = 3.35$
$m_b = 3.0$, $M_s = 2.35$



APPENDIX 4

Letter from K. Campbell to D.L. Bernreuter

United States Department of the Interior
GEOLOGICAL SURVEY
BOX 25046 M.S. 966
DENVER FEDERAL CENTER
DENVER, COLORADO 80225

IN REPLY REFER TO

Branch of Geologic Risk Assessment

December 8, 1986

Mr. Don Bernreuter
Lawrence Livermore Laboratory
P.O. Box 808, MS-196
Livermore, California 94550

Dear Don:

I reviewed my paper entitled "A Ground Motion Model for the Central United States Based on Near-Source Acceleration Data" that was published in the proceedings of the 1981 Knoxville,
Tennessee conference on Earthquakes and Earthquake Engineering: The Eastern U.S. My conclusion is that I would not recommend that it be used for estimating ground motion in the eastern U.S. The problem is that the anelastic attenuation coefficients used to develop the attenuation relationships are no longer thought to be valid.

I have not included any copies of my slides, since the slides by themselves are not meaningful. They require some descriptive text to be useful. Besides they came directly from my published papers on the subject.

Sincerely,

Ken

Kenneth W. Campbell

NRC FORM 335 (2-84) NRCM 1102, 3201, 3202 — U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

SEE INSTRUCTIONS ON THE REVERSE

1. REPORT NUMBER *(Assigned by TIDC, add Vol No., if any)*	NUREG/CR-5250 UCID-21517 Vol. 7
2. TITLE AND SUBTITLE	Seismic Hazard Characterization of 69 Nuclear Plant Sites East of the Rocky Mountains Questionnaires
3. LEAVE BLANK	
4. DATE REPORT COMPLETED	MONTH: November — YEAR: 1988
5. AUTHOR(S)	D.L. Bernreuter, J.B. Savy, R.W. Mensing, J.C. Chen
6. DATE REPORT ISSUED	MONTH: January — YEAR: 1989
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11a. TYPE OF REPORT	Technical
b. PERIOD COVERED *(Inclusive dates)*	October 1986-October 1988
12. SUPPLEMENTARY NOTES	

13. ABSTRACT *(200 words or less)*

The EUS Seismic Hazard Characterization Project (SHC) is the outgrowth of an earlier study performed as part of the U.S. Nuclear Regulatory Commission's (NRC) Systematic Evaluation Program (SEP). The objectives of the SHC were: (1) to develop a seismic hazard characterization methodology for the region east of the Rocky Mountains (EUS), and (2) the application of the methodology to 69 site locations, some of them with several local soil conditions. The method developed uses expert opinions to obtain the input to the analyses. An important aspect of the elicitation of the expert opinion process was the holding of two feedback meetings with all the experts in order to finalize the methodology and the input data bases. The hazard estimates are reported in terms of peak ground acceleration (PGA) and 5% damping velocity response spectra (PSV).

A total of eight volumes make up this report which contains a thorough description of the methodology, the expert opinion's elicitation process, the input data base as well as a discussion, comparison and summary volume (Volume VI).

Consistent with previous analyses, this study finds that there are large uncertainties associated with the estimates of seismic hazard in the EUS, and it identifies the ground motion modeling as the prime contributor to those uncertainties.

The data bases and software are made available to the NRC and to the public uses through the National Energy Software Center (Argonne, Illinois).

14. DOCUMENT ANALYSIS – a. KEYWORDS/DESCRIPTORS	Seismic hazard, Eastern U.S., ground motion
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